Understanding and Calibrating the Offset and Gain for ADC Systems

TIPL 4202
TI Precision Labs – ADCs

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Presented by Peggy Liska

Offset Voltage Calculation

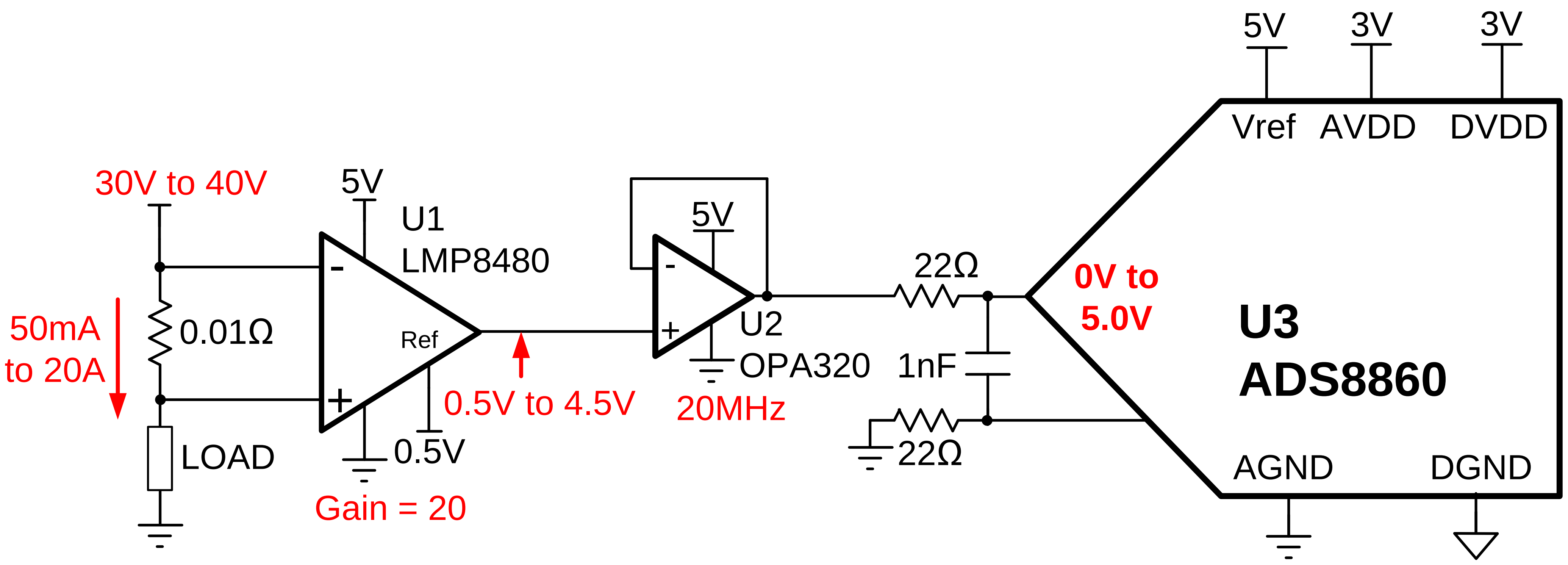
Device	PARAMETER		MIN	TYP	MAX	UNITS
LMP8481	V_{OS}	Offset	-265	±80	+265	µV
OPA320	V_{OS}	Offset	-150	±40	+150	µV
ADS8860	E_O	Offset	-2	±0.8	+2	mV

Typical offset at ADC Input

$$V_{osT} = \sqrt{(20 \cdot V_{osINA})^2 + (V_{osOPA})^2 + (V_{osADS})^2}$$

$$V_{osT} = \sqrt{(20 \cdot 80\mu V)^2 + (40\mu V)^2 + (1mV)^2}$$

$$V_{osT} = \pm 1.887mV$$



Number of Standard Deviations	Probability Inside Limit
±1·σ	68.27%
±2·σ	95.45%
±3·σ	99.73%
±4·σ	99.9937%
±5·σ	99.99994%
±6·σ	≈100%

Gain Error Calculation

Device	PARAMETER		MIN	TYP	MAX	UNITS
R1	E_R	Tolerance	-0.1		+0.1	%
LMP8481	E_G	Gain Error	-0.6		+0.6	%
ADS8860	E_G	Gain Error	-0.01	±0.005	+0.01	%

Absolute Worse Case Gain Error

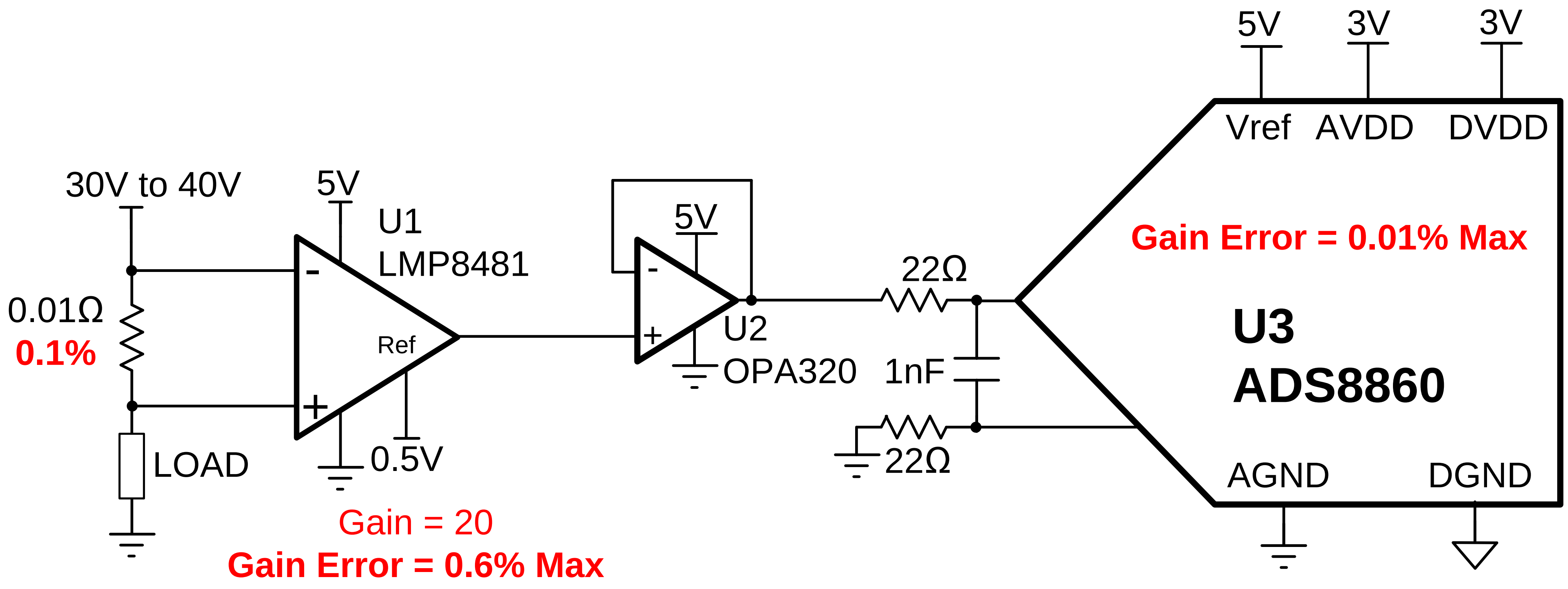
$$V_{osT} = E_{R1} + E_{GU1} + E_{GU3}$$

$$V_{osT} = 0.1\% + 0.6\% + 0.01\% = \pm 0.71\%$$

Statistical Worse Case Gain Error

$$V_{osT} = \sqrt{(E_{R1})^2 + (E_{GU1})^2 + (E_{GU3})^2}$$

$$V_{osT} = \sqrt{(0.1\%)^2 + (0.6\%)^2 + (0.01\%)^2} = \pm 0.608\%$$

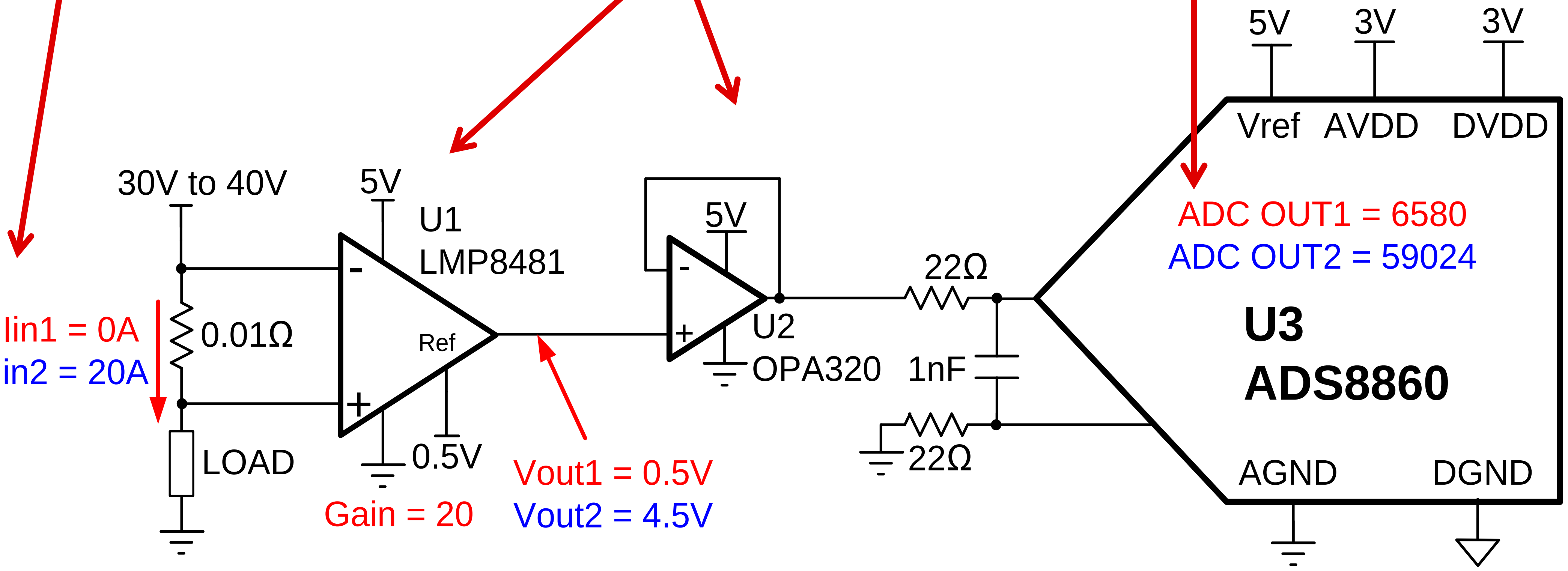


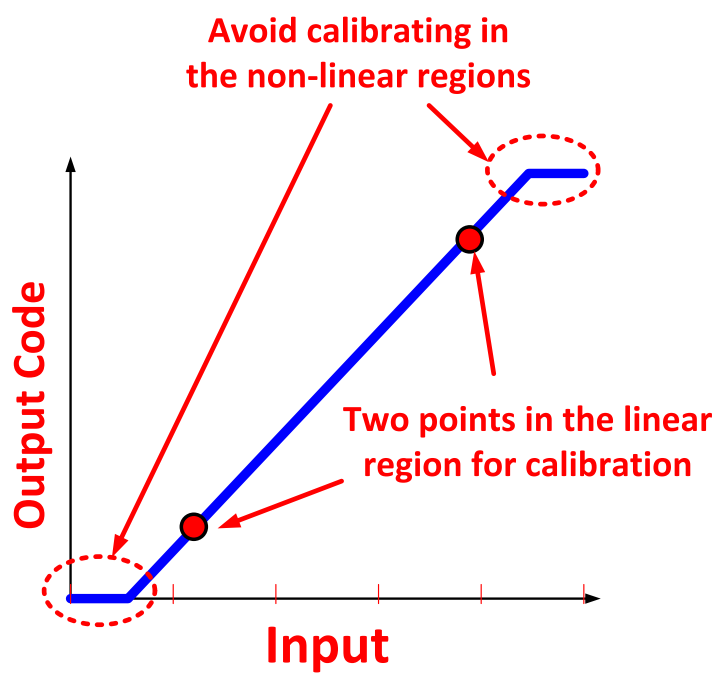
Offset and Gain Calibration: two test signals

Two Precision inputs applied

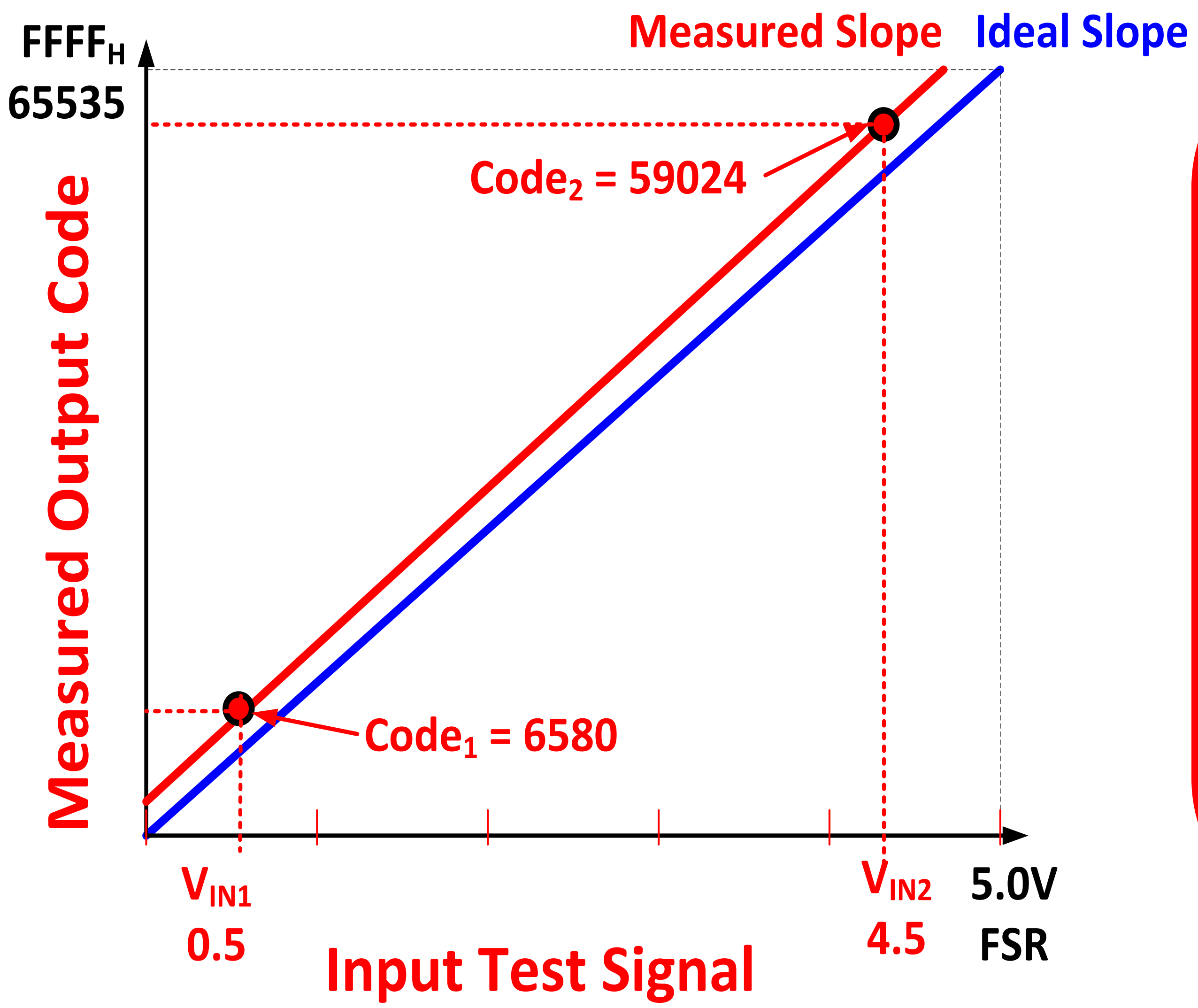
Make sure amplifiers are in linear range

Average code read





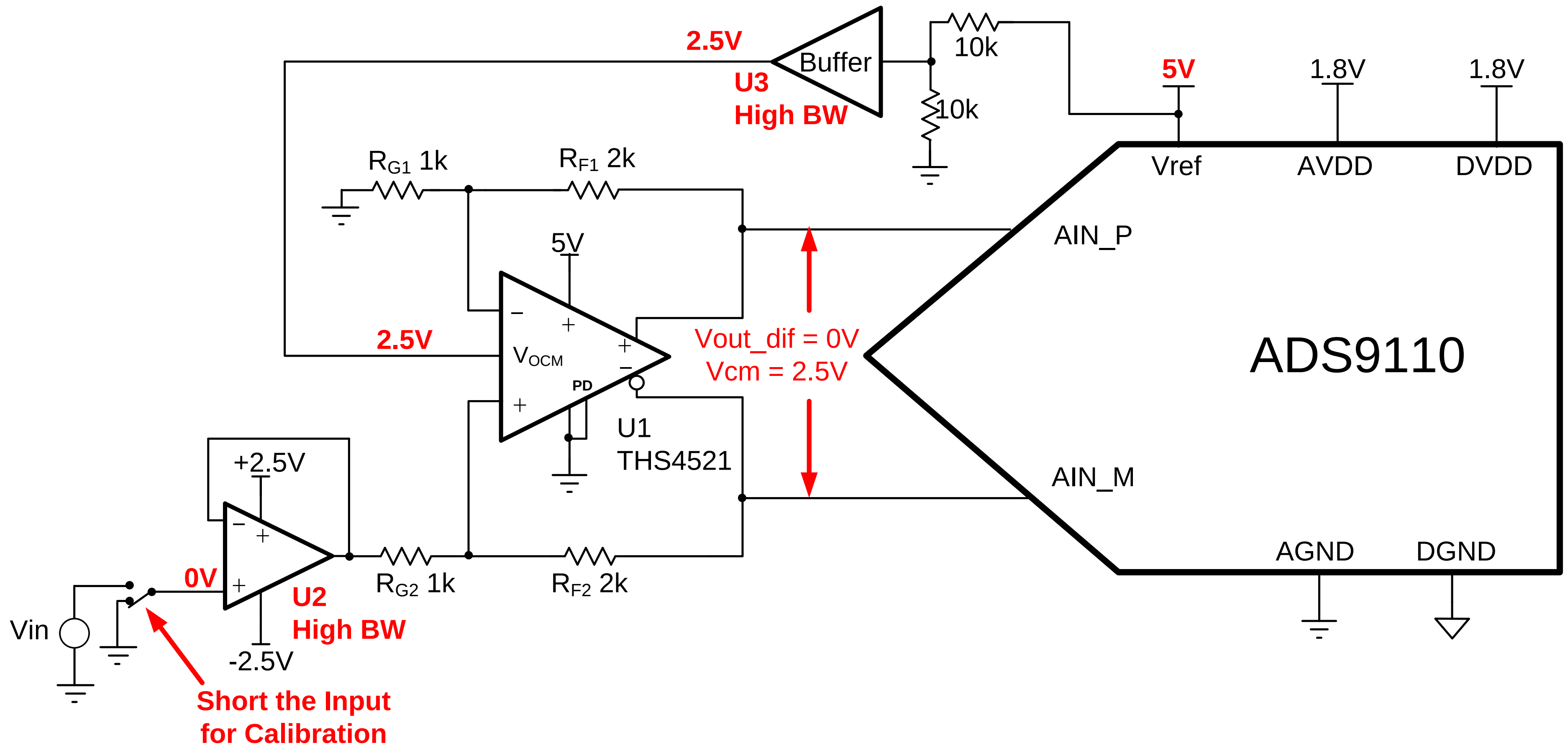
Calibration Example

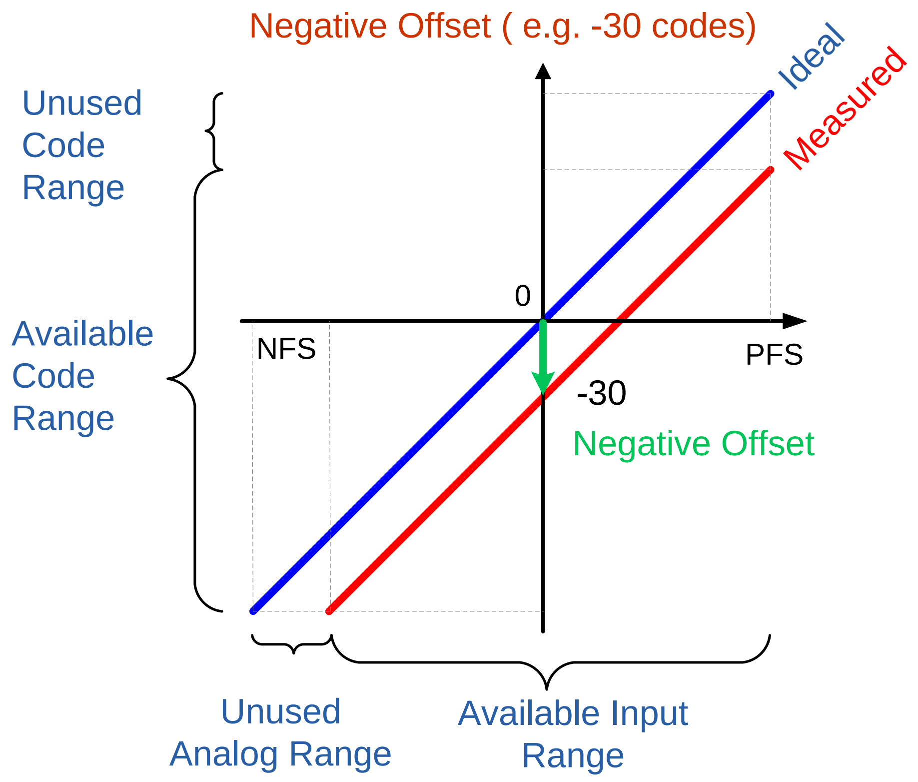


Example calculation for Offset and Gain Error:

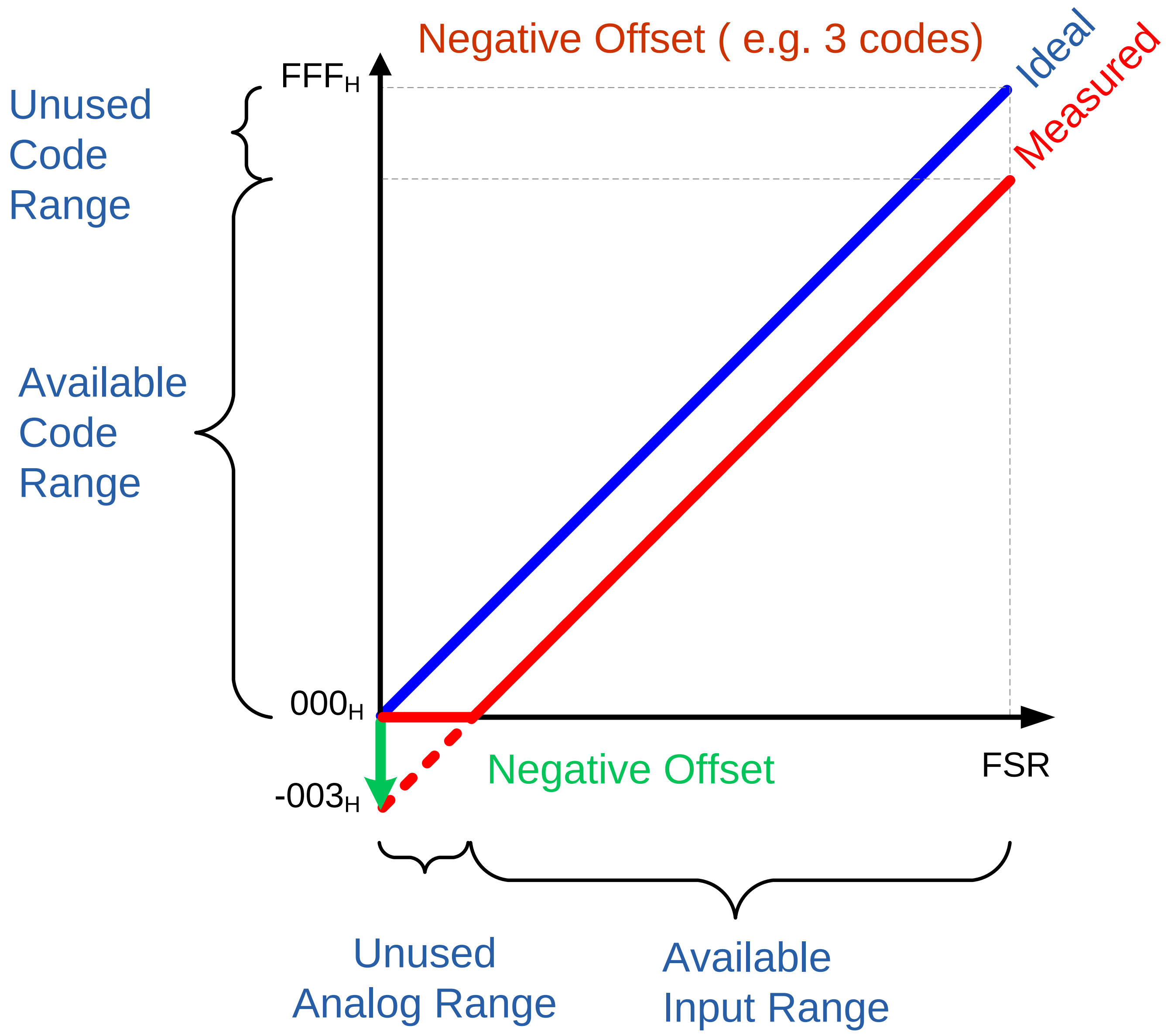
$V_{IN1} = 0.5V$	Apply 0A
$V_{IN2} = 4.5V$	Apply 20A
$m_m = \frac{Code_2 - Code_1}{V_{IN2} - V_{IN1}} = \frac{59024 - (6580)}{4.5 - 0.5} = 13111$	Compute Slope based on codes
$b_m = Code_1 - m_m \cdot V_{IN1} = 6580 - 13111 \cdot 0.5 = 24.5$	Offset
$V_{IN\_applied} = 2.0V$	Example Input
$Code = 26246$	Output code
$V_{IN\_uncal} = Code \cdot LSB = 26246 \cdot 76.029\mu V = 2.002V$	Uncalibrated 2mV error
$V_{IN} = \frac{Code - b_m}{m_m} = \frac{26246 - (24.5)}{13111} = 2.0000V$	Calibration eliminates error

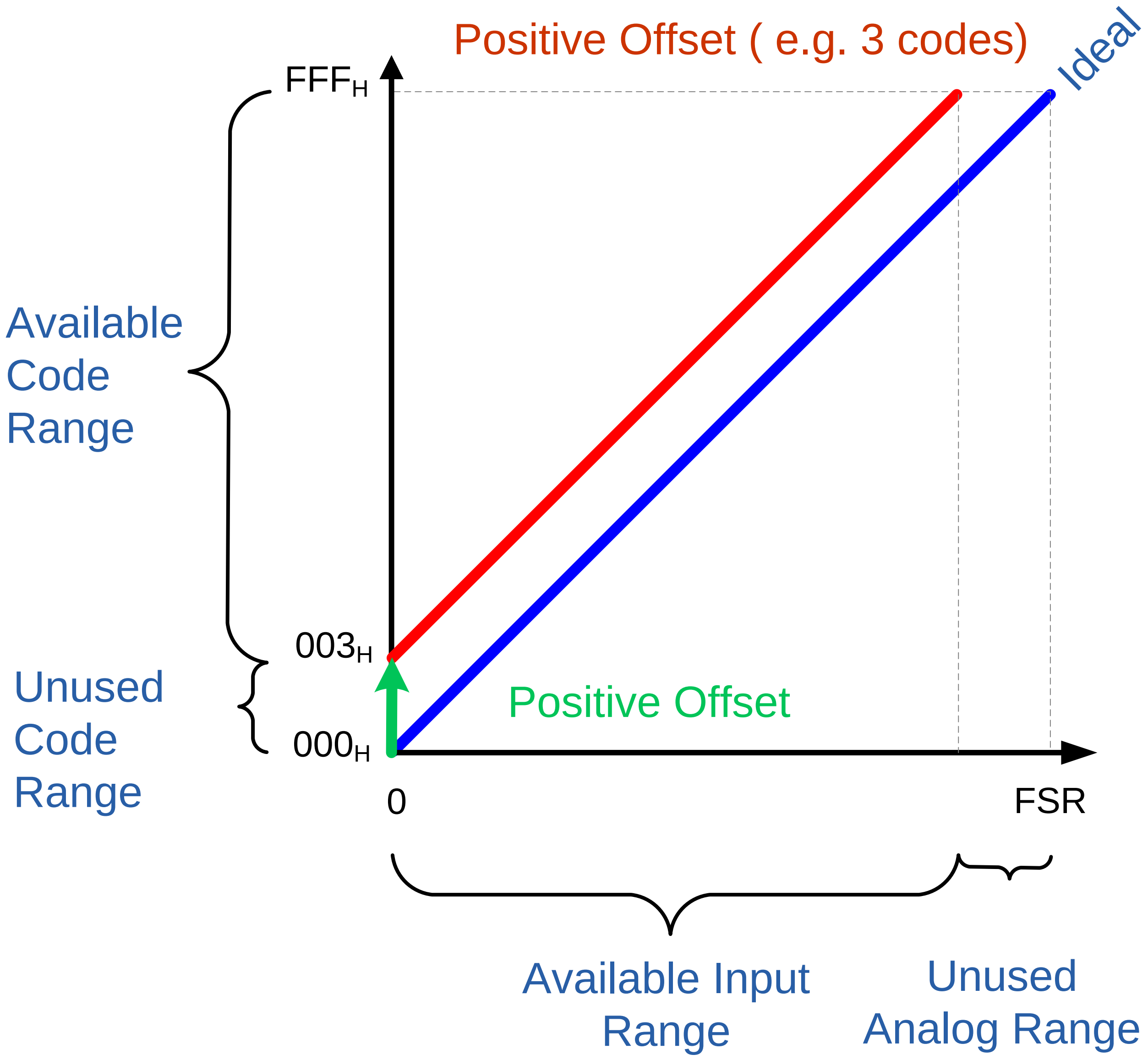
Offset calibration with short



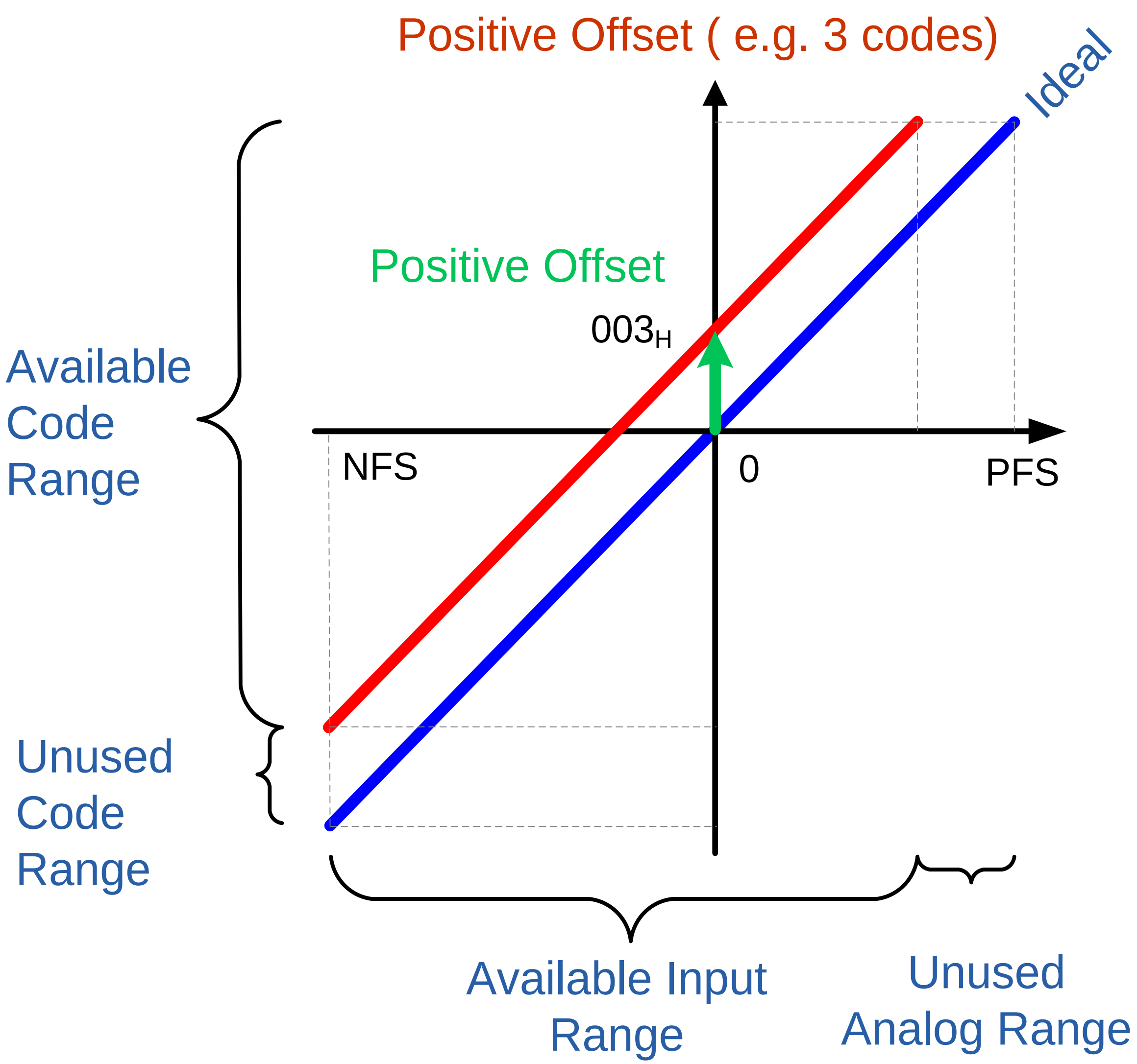


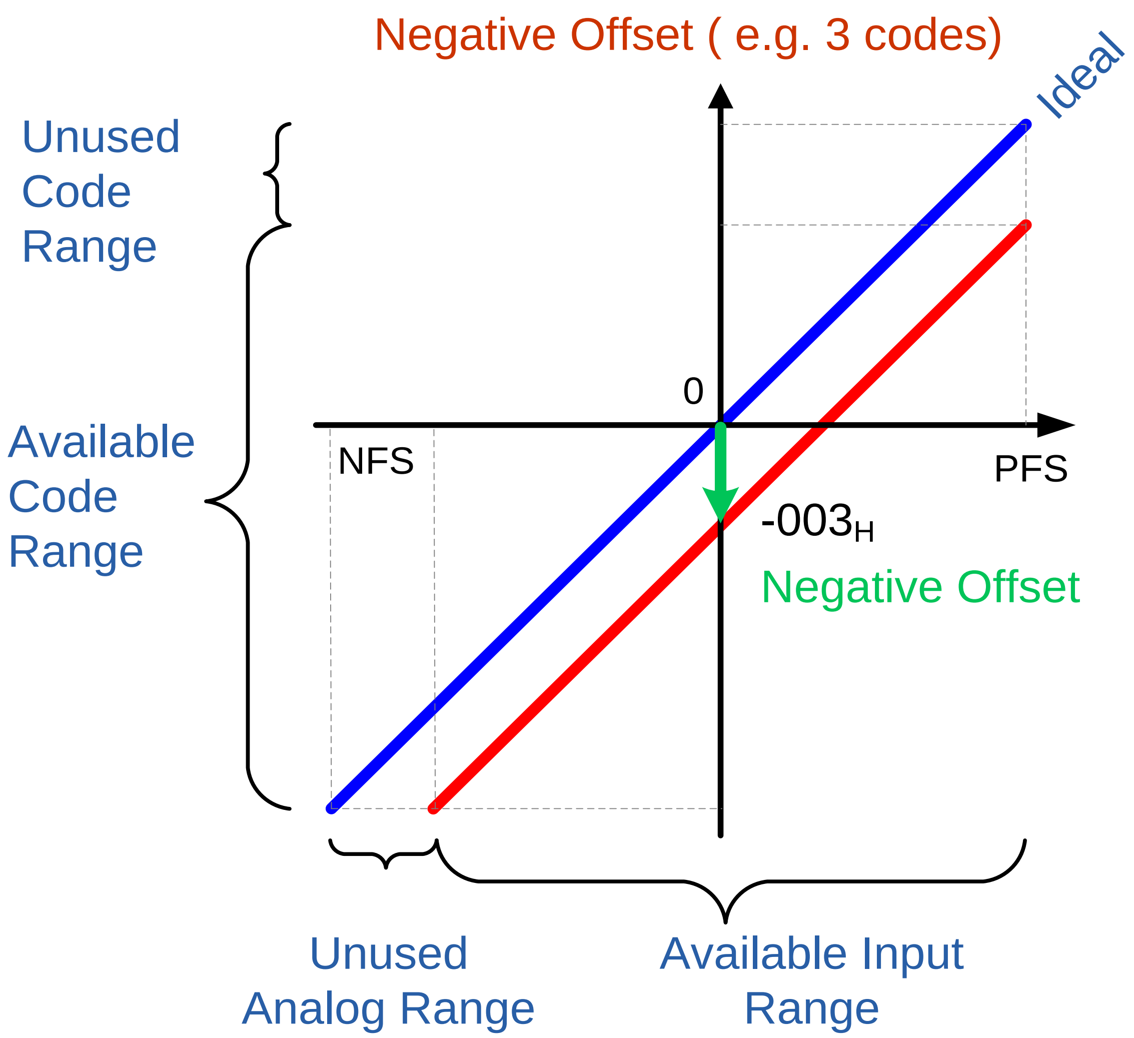
Offset Error – Unipolar





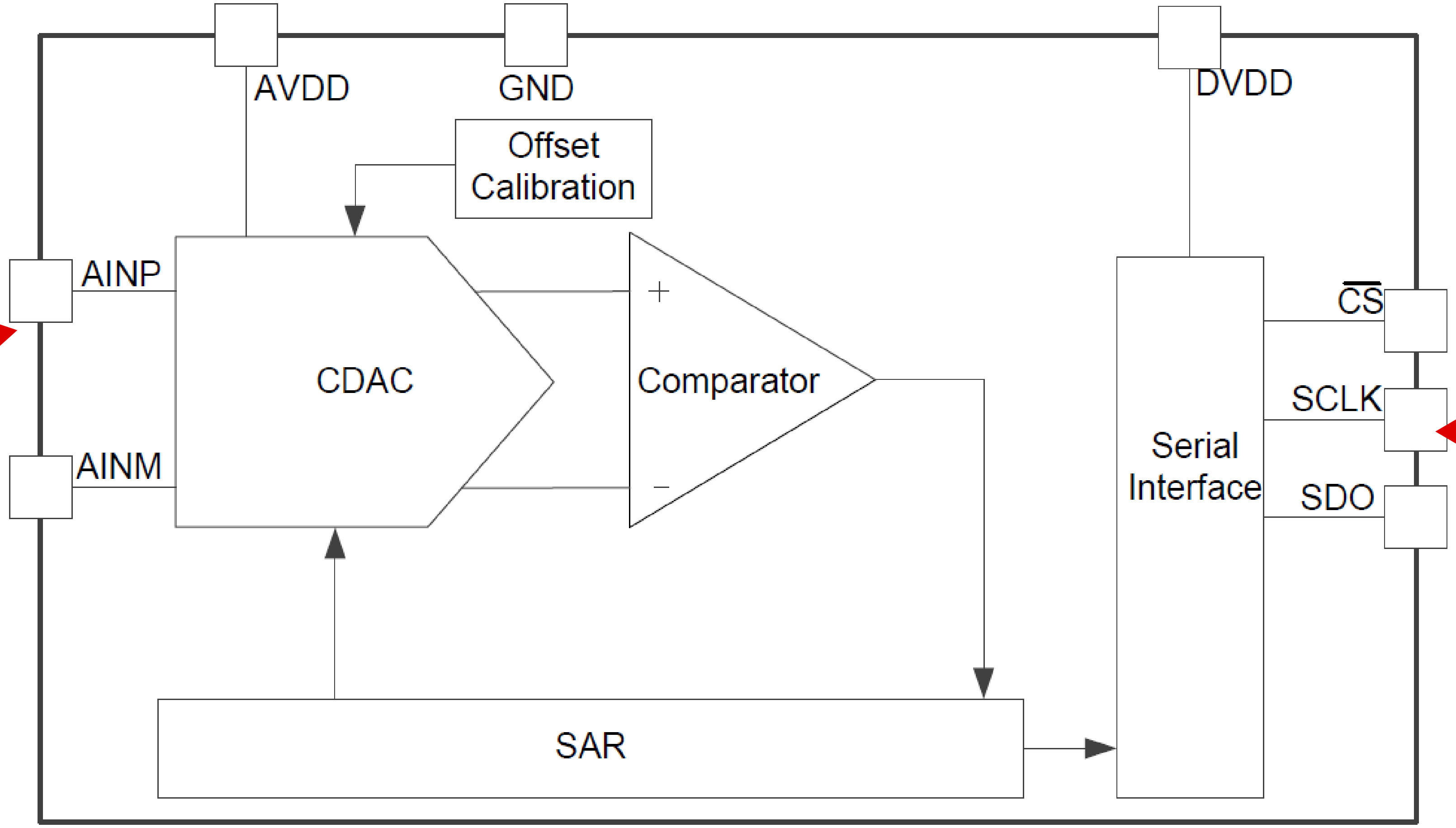
Offset Error – Bipolar, or Unipolar with Differential input range





Automatic Offset Calibration: ADS7042

Inputs disconnected during calibration



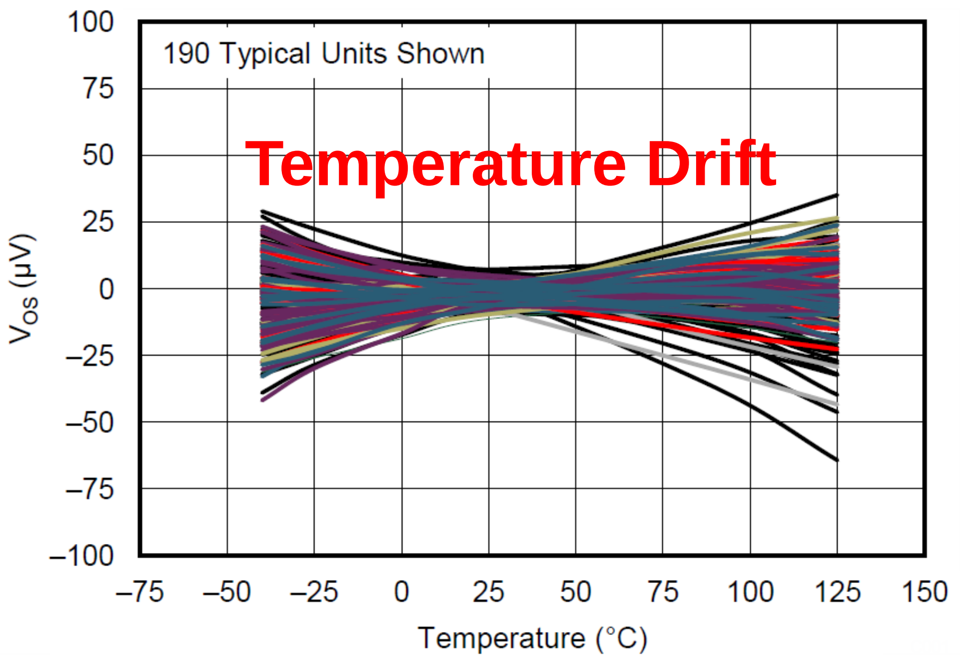
Digital command initiates calibration

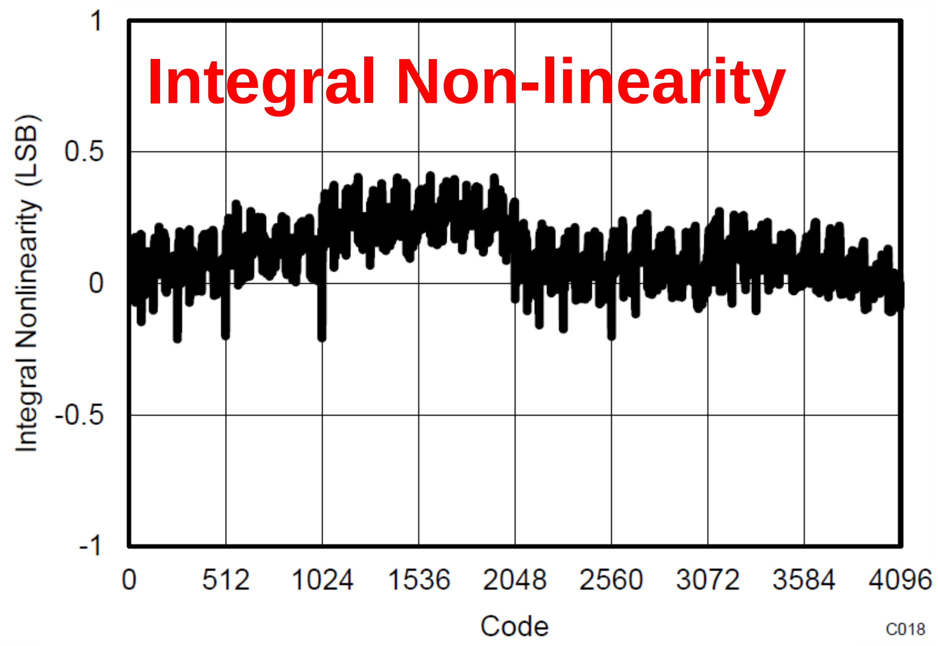
PARAMETER	MIN	TYP	MAX	UNIT
Uncalibrated Offset		±12		LSB
Calibrated Offset	-3	±0.5	+3	

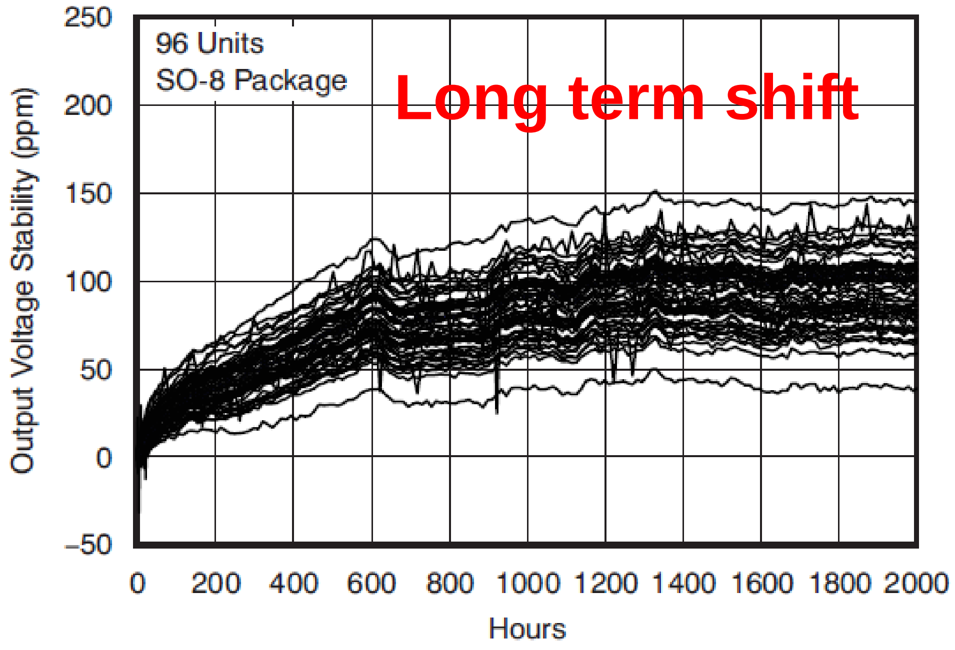
Offset correction stored in register and automatically subtracted after each conversion

Error Sources that are difficult to Calibrate

- Temperature Drift
- Non-linearity
- Long term shift (Aging)
- Hysteresis
- Noise







Thanks for your time!
Please try the quiz.

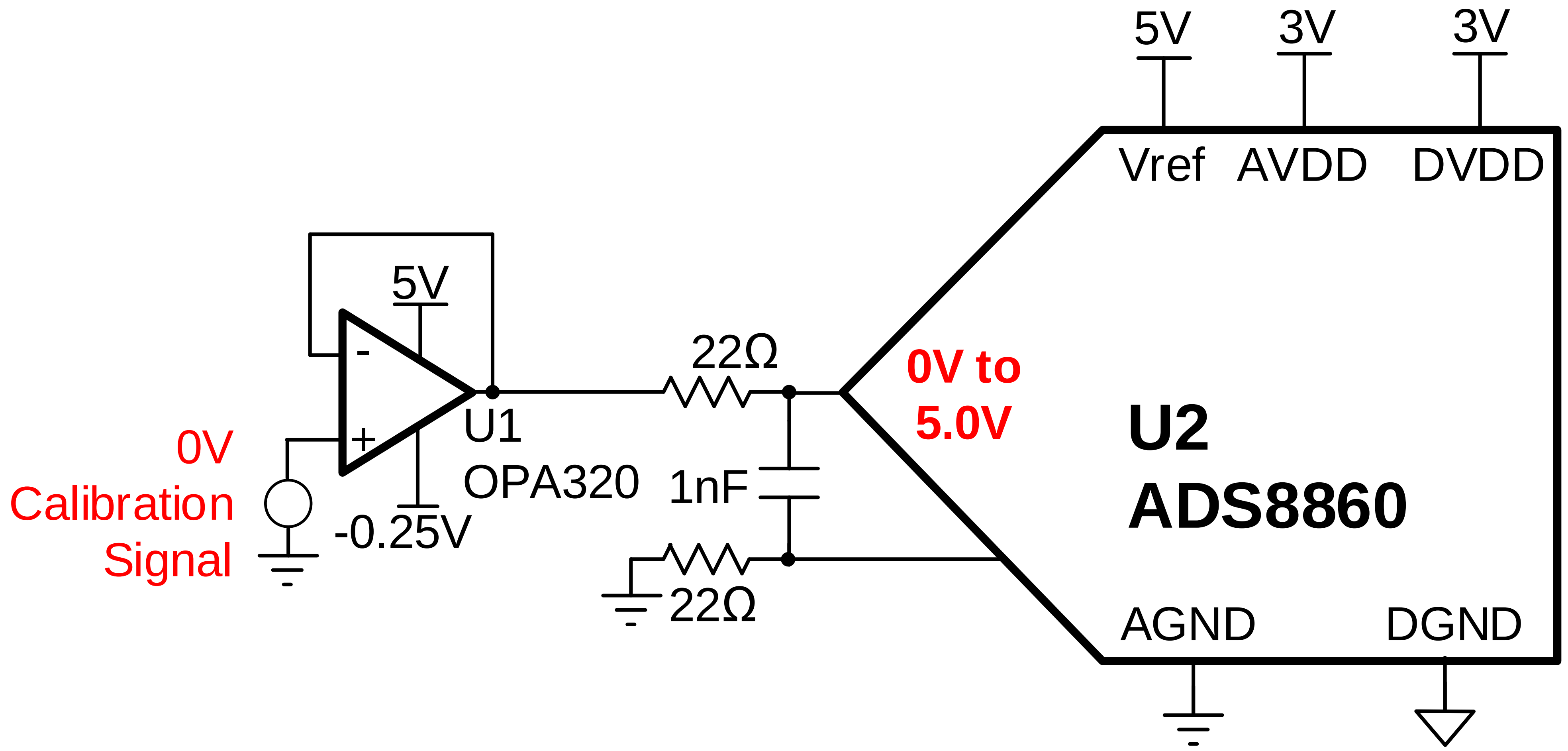
Quiz: Understanding and Calibrating the Offset and Gain for ADC Systems

TIPL 4202
TI Precision Labs – ADCs

Created by Art Kay

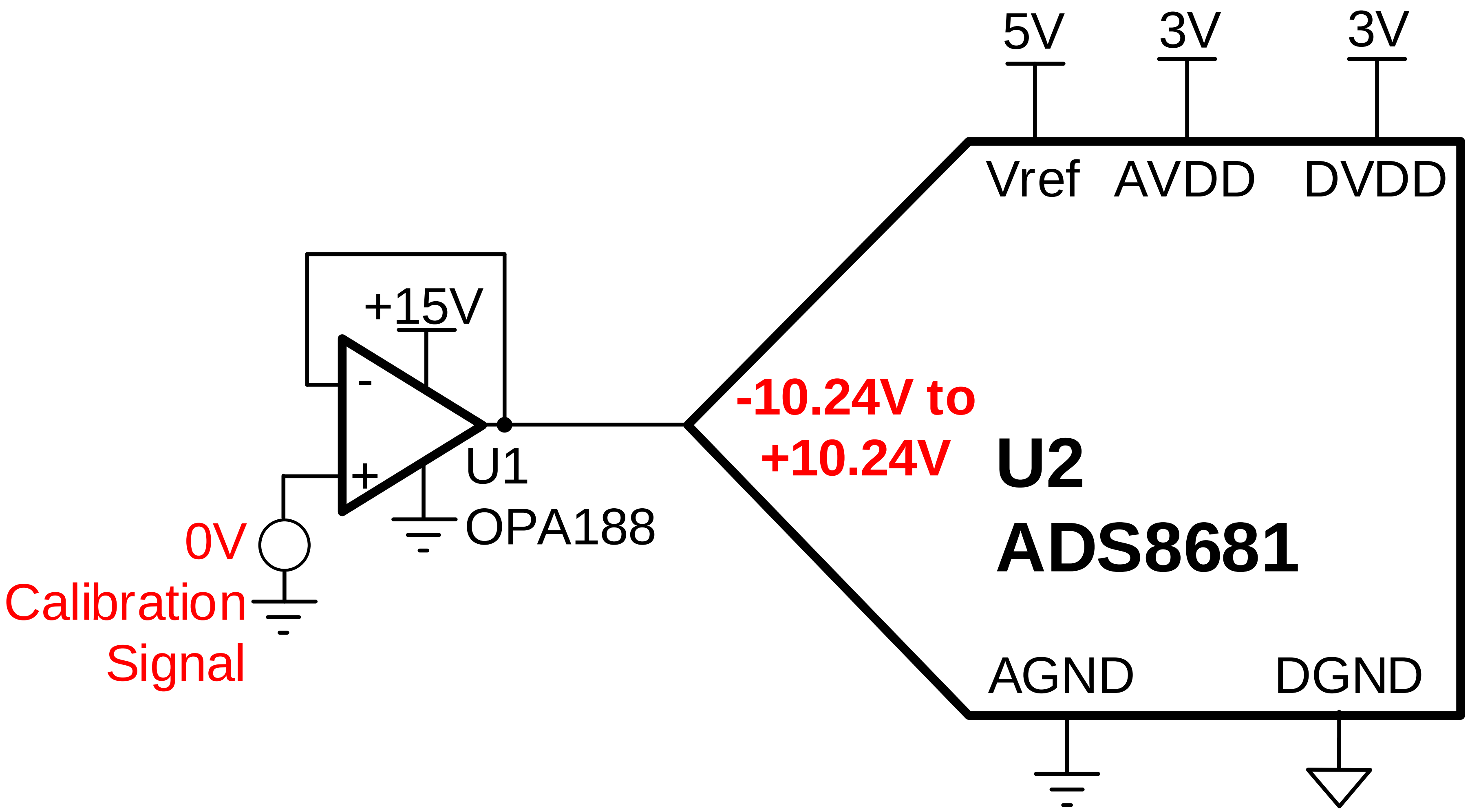
Quiz: Calibration

1. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is 0V to 5V.



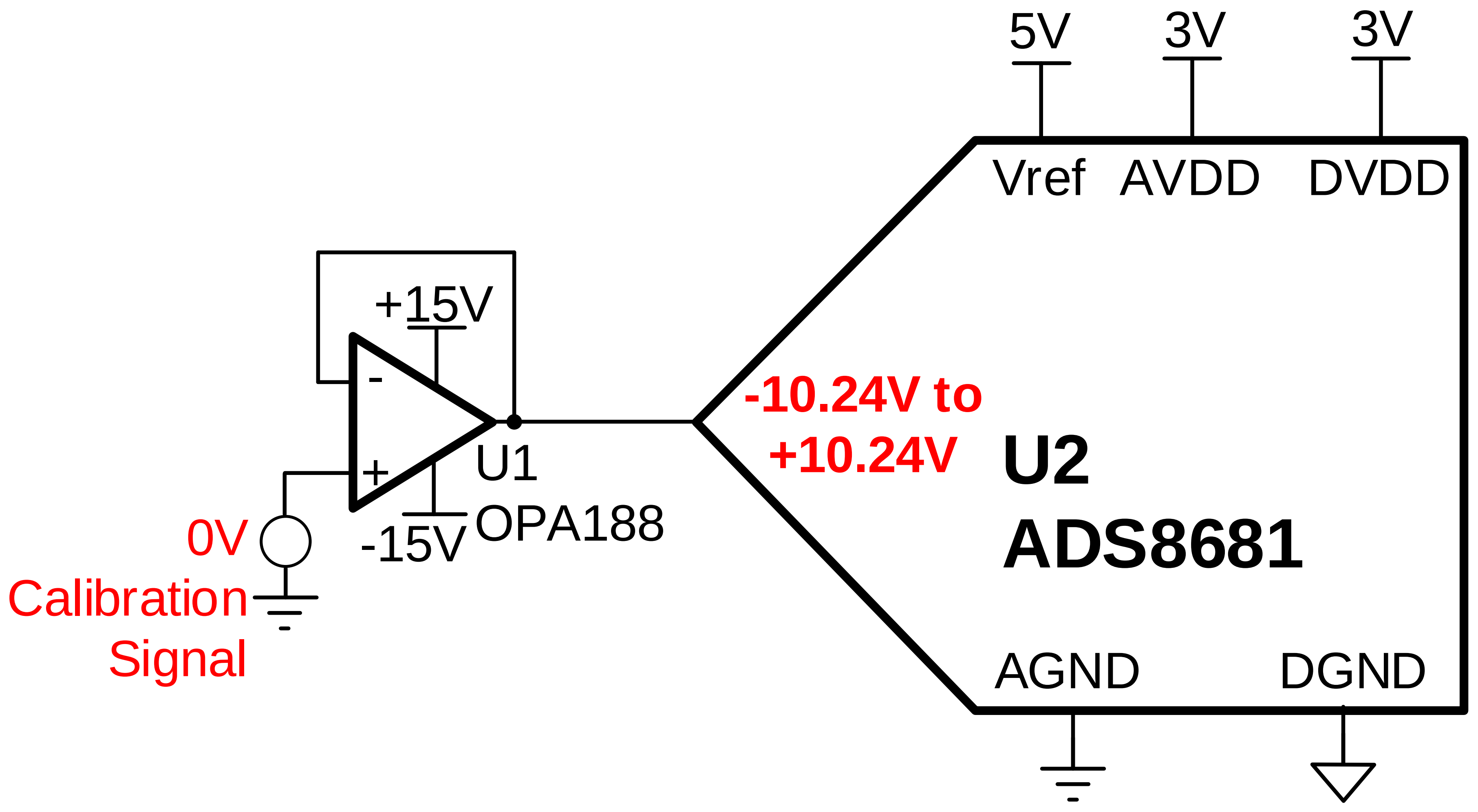
Quiz: Calibration

2. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is -10.24V to 10.24V.



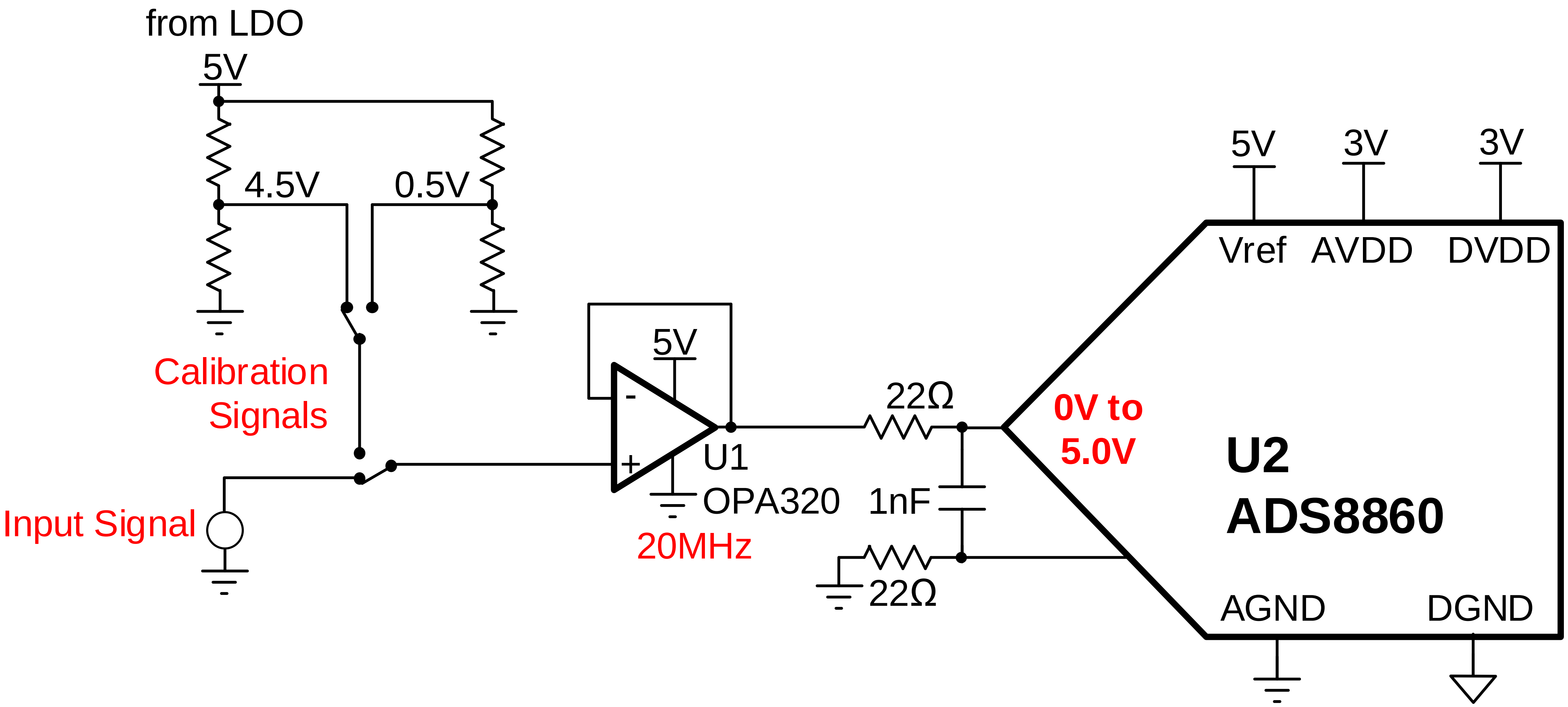
Quiz: Calibration

3. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is -10.24V to 10.24V.



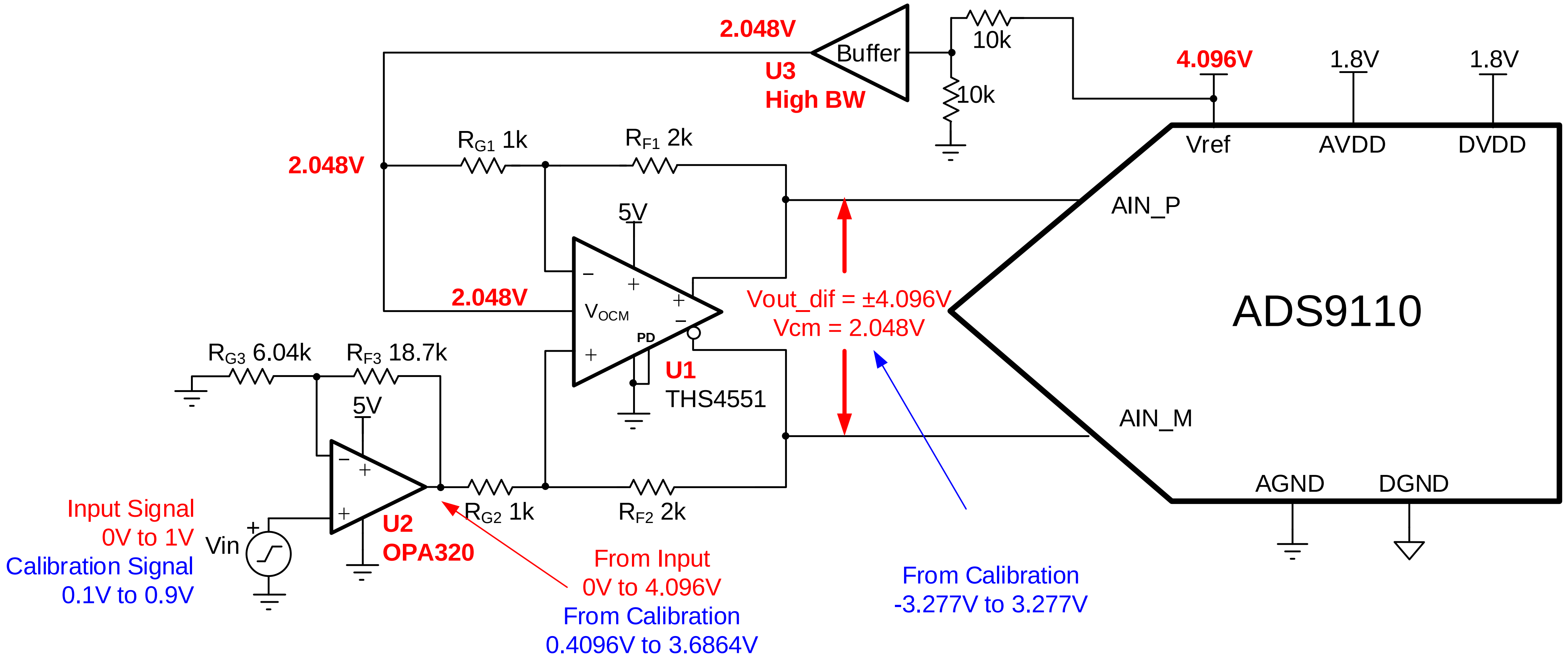
Quiz: Calibration

4. The circuit below has some switches that allow calibration signal to be applied to the system. The calibration signals are generated using a 5V LDO output and a voltage divider. What are some potential issues with this calibration method?



Quiz: Calibration

5. Below is a circuit that is scaled so that the ADC is at negative full scale for a system input of 0V, and at positive full scale for a system input of 1V. Calibration signals of 0.1V and 0.9V are applied to the input and the output codes are read. Use this information to create calibration coefficients. Also, what is the calibrated system input for an output code of 32000_{10}. Finally, what would the error have been without calibration.



Vin = 0.1V

Code = -104820_{10}

Vin = 0.9V

Code = 104895_{10}

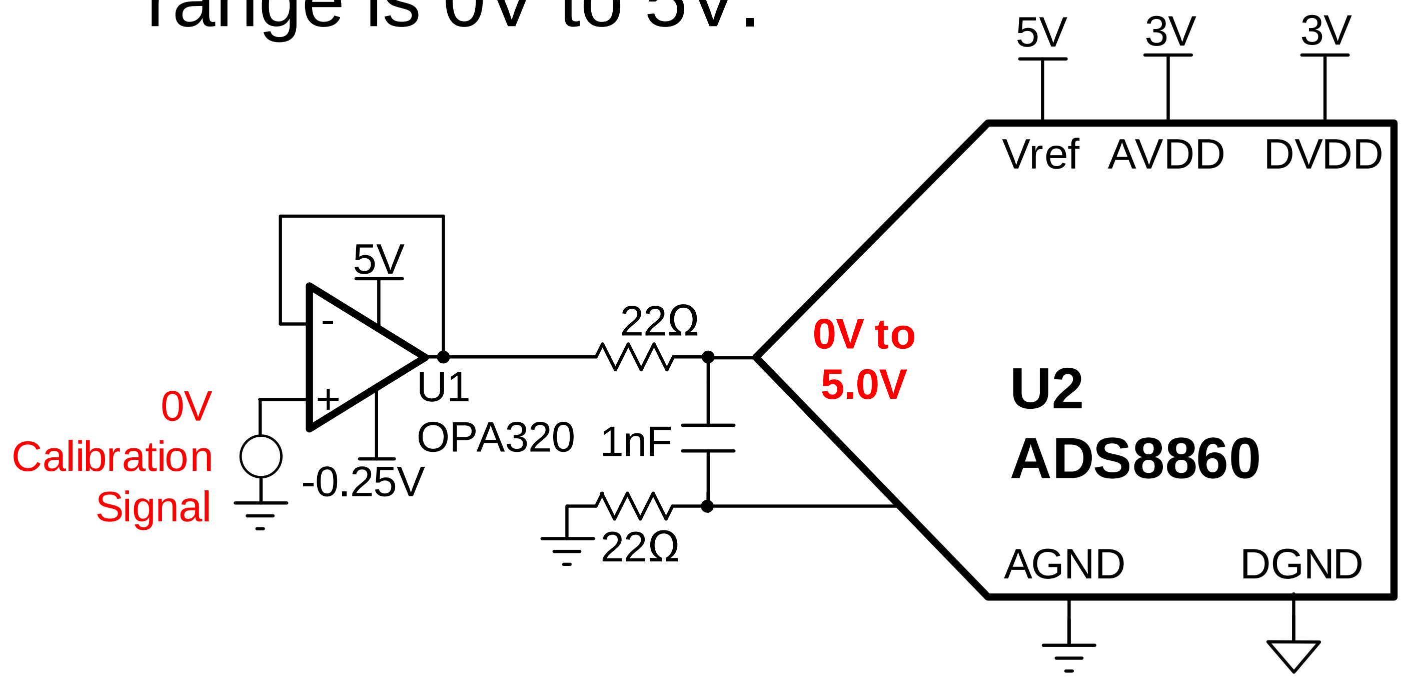
For Code = 32000_{10}

What is Vin = ?

Solutions

Quiz: Calibration

1. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is 0V to 5V.



ANS: No. Look at OPA:
Applying 0V to the amplifier will drive the its output towards 0V. For this example the negative supply is -0.25V this allows swing of the op amp to 0V. Note the output swing and common mode aren't limited (see table below). Thus, the op amp is not the limitation.

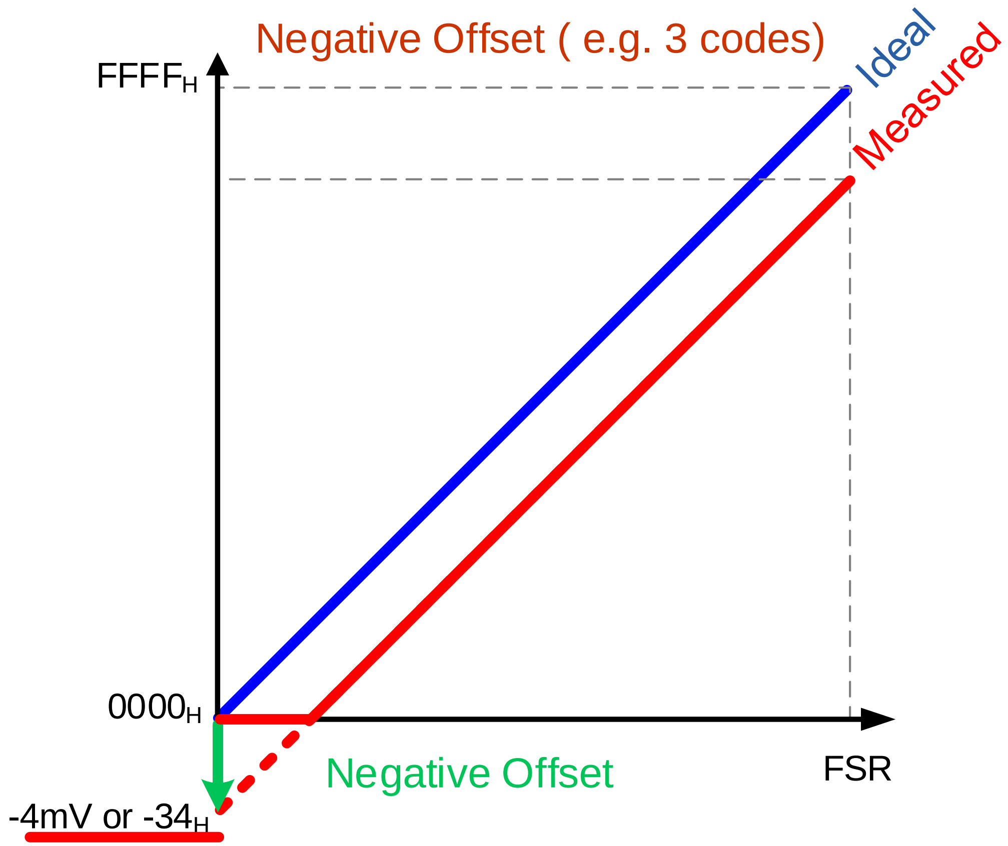
PARAMETER OPA320		MIN	TYP	MAX	UNIT
Vo	Voltage output swing from both rails		10	20	mV
Vcm	Common mode range	(V-) - 0.1		(V+) + 0.1	V

Quiz: Calibration

1. **Continued:** The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is 0V to 5V.

ANS: No. Look at ADC:

Applying 0V to the ADC input should ideally give the offset of the data converter. This works if the offset is positive. However, the data converter can have a negative offset. In this case the data converter will read 0000_H as it cannot read below zero. Thus, this calibration scheme will not work as it cannot measure negative ADC offset.

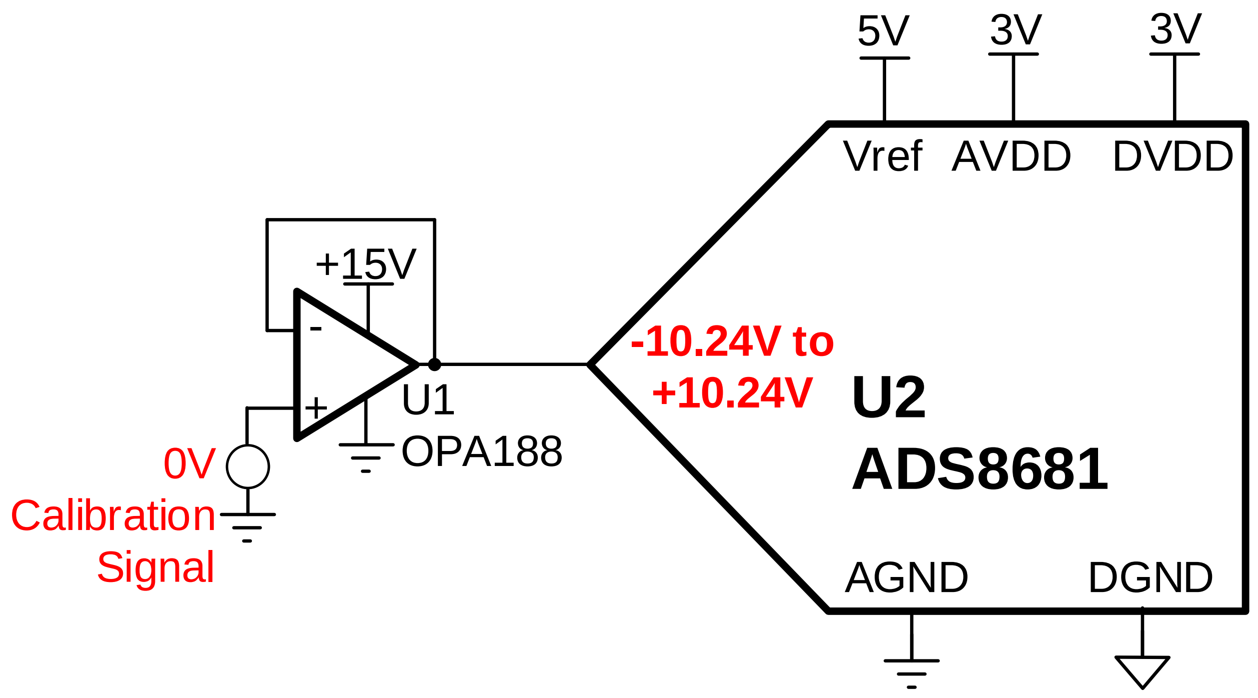


The ADC cannot read any code less than 0000_H, but the offset is actually -34_H (-4mV).

PARAMETER OPA320	MIN	TYP	MAX	UNIT
Eo Offset Error	-4	±1	+4	mV

Quiz: Calibration

2. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is -10.24V to 10.24V.

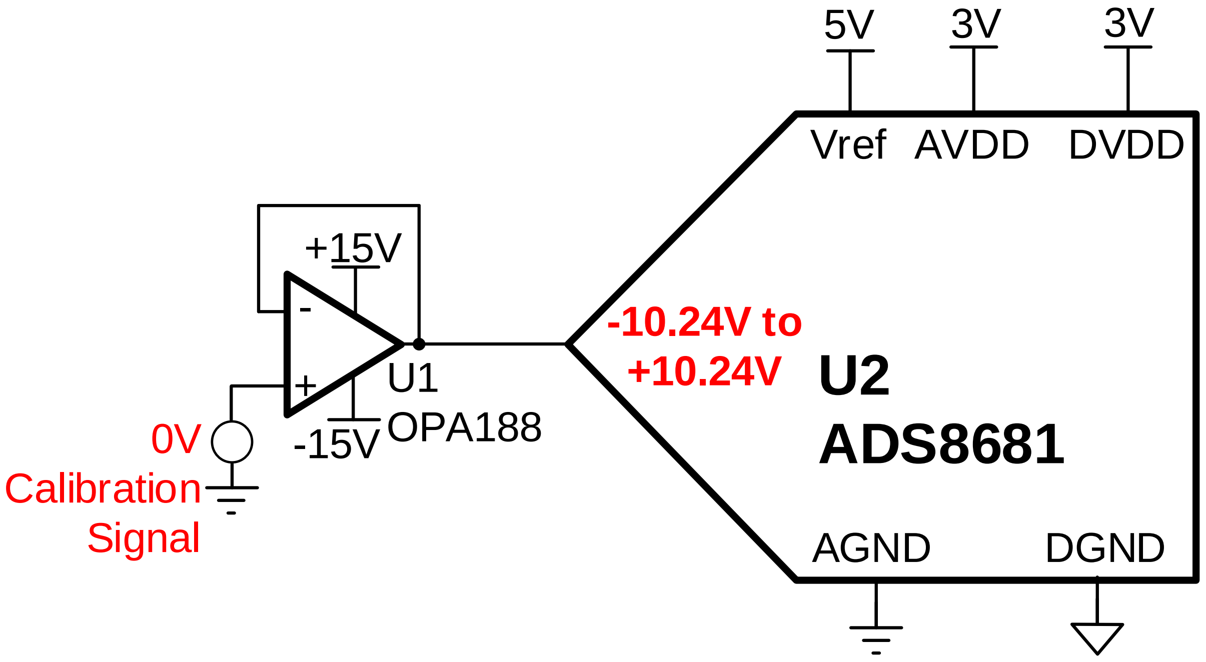


ANS: No. Look at OPA:
Applying 0V to the amplifier will drive the its output towards 0V. For this example the negative supply is 0V. The output swing limitation will prevent linear operation 15mV from ground. Thus, the offset of this amplifier configuration cannot be measure by applying 0V to the input.

PARAMETER OPA188		MIN	TYP	MAX	UNIT
Vo	Voltage output swing from both rails		5	15	mV
Vcm	Common mode range	(V-)		(V+) – 1.5	V

Quiz: Calibration

3. The goal is to calibrate the offset voltage for this system. Can we do this by applying 0V to the input and measuring the output code? Note the ADC input range is -10.24V to 10.24V.

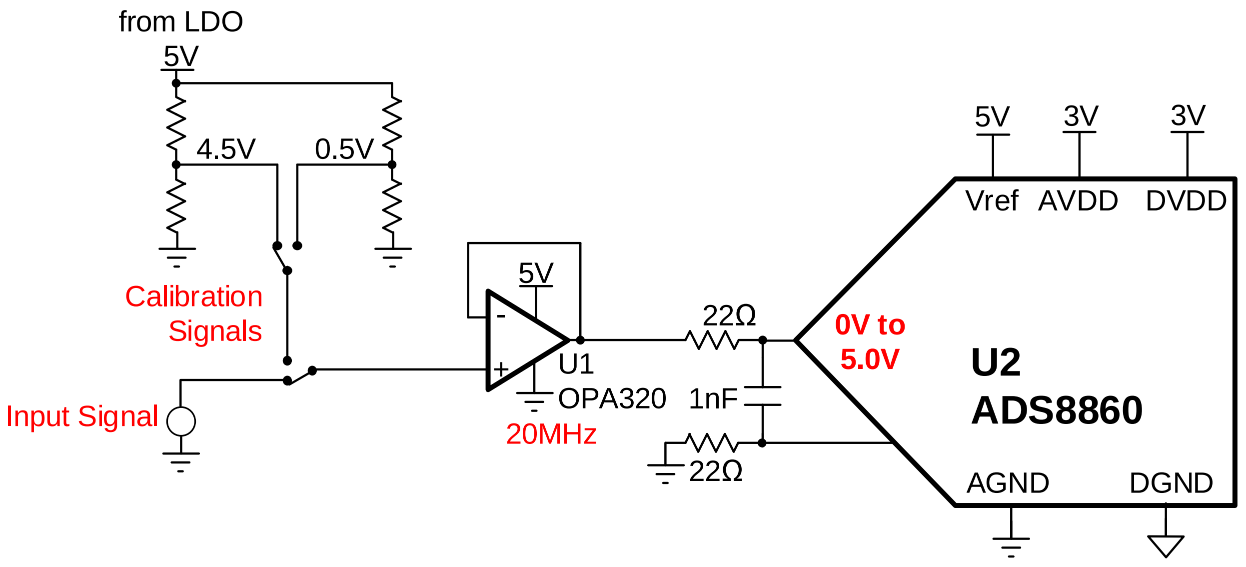


ANS: Yes

The amplifier has dual supply's, so applying 0V to the input is well within the linear range. Thus the amplifiers offset can be directly measured by grounding the input. The ADC is a bipolar input, so applying 0V to the input will allow reading of both positive an negative offsets without limitations.

Quiz: Calibration

4. The circuit below has some switches that allow calibration signal to be applied to the system. The calibration signals are generated using a 5V LDO output and a voltage divider. What are some potential issues with this calibration method?



ANS: Potential issues

1. The LDO 5V output is used to generate the calibration voltages. This is unlikely to have the accuracy, drift, noise, and long term stability required for calibration.
2. The voltage dividers need to be very accurate low drift resistors.
3. Make sure error sources from the switches are considered. Switches have leakage, non-linear impedance, capacitance, and other nonidealities.

Quiz: Calibration

5. Calibrate given inputs and circuit. What is input voltage for Code = 32000_{10}. What would the error be without calibration?

Vin = 0.1V
Code = -104820_{10}
Vin = 0.9V
Code = 104895_{10}

For Code = 32000_{10}
What is Vin = ?

Calibration Inputs and Codes

$V_{in1} := 0.1V \qquad Code_1 := -104720$

$V_{in2} := 0.9V \qquad Code_2 := 104995$

Find Calibration Coeficients

$$m_m := \frac{Code_2 - Code_1}{V_{in2} - V_{in1}} = 2.621 \times 10^5 \frac{1}{V}$$

$$b_m := Code_1 - m_m \cdot V_{in1} = -1.309 \times 10^5$$

Use coeficients to find Vin for Code = 32000

$Code := 32000$

$$V_{in} := \frac{Code - b_m}{m_m} = 0.621546\,V$$

Uncalibrated Vin Calculation Assuming ideal gain and offset

$$LSB = 2 \cdot \frac{V_{ref}}{2^{18}}$$ From data sheet

$$V_{adc} = Code \cdot LSB$$

$$V_{adc} := Code \cdot \frac{4.096V \cdot 2}{2^{18}} = 1.000000\,V$$

$$V_{adc} = G_{FDA} \cdot G_{OPA} \cdot V_{in} - G_{FDA} \cdot \frac{V_{ref}}{2}$$

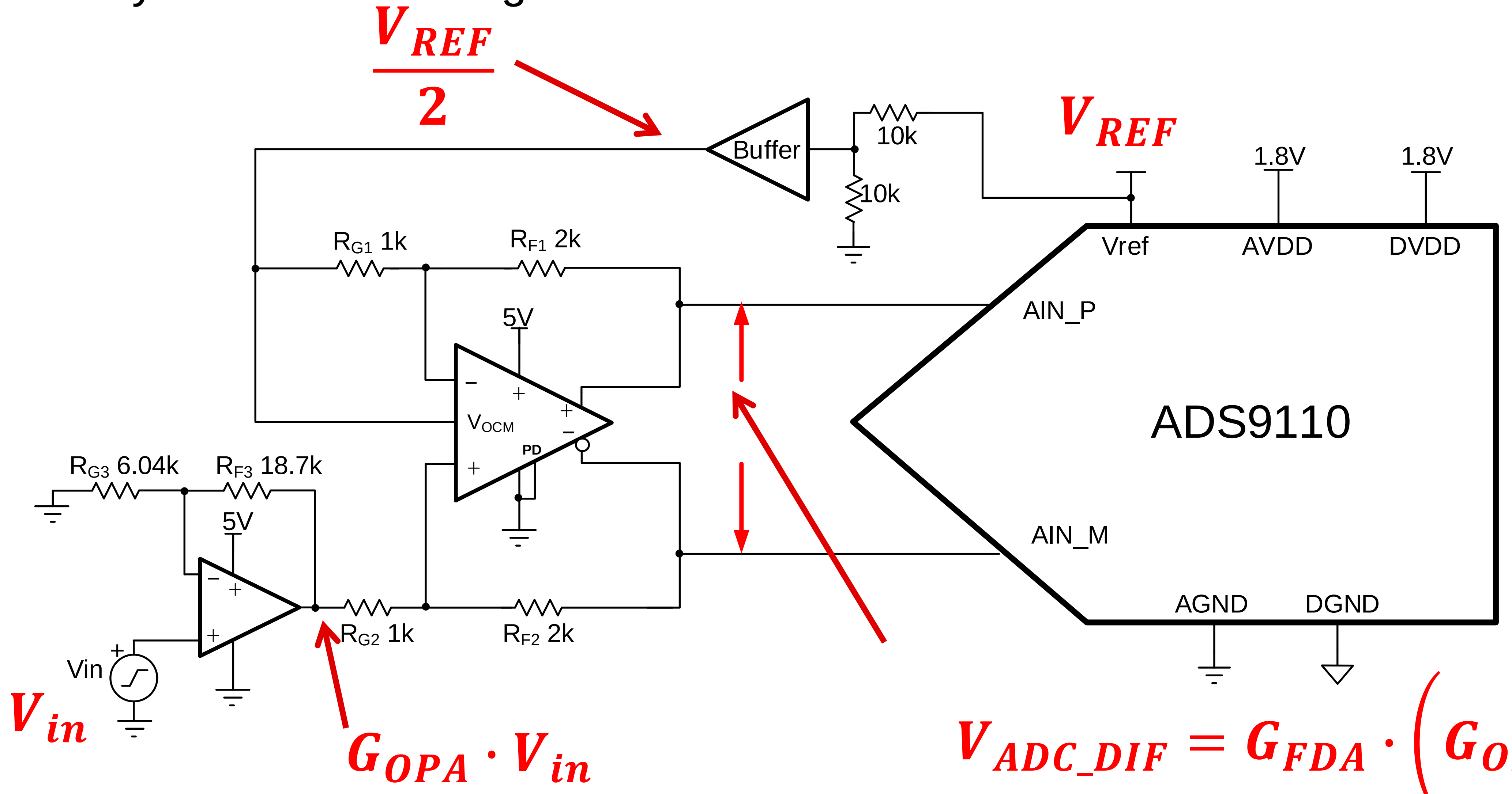
$$V_{adc} = (2) \cdot (4.096) \cdot V_{in} - (2) \cdot \frac{4.096V}{2}$$

$$V_{in\_no\_cal} := \frac{V_{adc}}{(2 \cdot 4.096)} + 0.5V = 0.622070\,V$$

$$Error := \frac{V_{in\_no\_cal} - V_{in}}{V_{in}} \cdot 100 = 0.084 \quad \%$$

Quiz: Calibration

5. Regarding the math on the previous slide. The transfer function to the FDA circuit is a little tricky and the math is given below.



Solve for input

$$V_{IN} = \frac{V_{ADC\_DIF}}{2 \cdot 4.096} + 0.5V$$

$$V_{ADC\_DIF} = G_{FDA} \cdot \left(G_{OPA} \cdot V_{IN} - \frac{V_{REF}}{2} \right)$$

$$V_{ADC\_DIF} = 2 \cdot (4.096 \cdot V_{IN} - 2.048)$$