Calibration and Accuracy

ECE 492 - Spring 2015

Abstract

This document outlines the various sensors involved in the LFEV, including their margin of error as well as how they are calibrated.

Revision 2.0.0
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Introduction

This document outlines how each group plans to evaluate the accuracy of the measurements made in terms of its error. This document will outline the uncertainty associated in all measurands. It will include analytical estimates of measurement uncertainty and a justification as to why that amount of uncertainty is acceptable. This document will work alongside the Acceptance Test Plan (ATP) for testing purposes to demonstrate that uncertainty verified in practice is within the analytical range and acceptable.

This document should be referred to before any modification is made to either the sensors or the software they interface with.

It is a basic truth of science and engineering that nothing can be measured with absolute certainty. There always exists some uncertainty associated with a measurement. Two types of error are typically identified. Systematic error occurs because of some inherent bias in the system, the environment, or the measurement technique, and affects the placement of the statistical mean of the measurements relative to the true value. Random error occurs because of disturbances that affect single measurements, and affects the standard deviation of the measurements from the true value. The goal of calibration is to minimize the systematic error in a given system.

The concept of calibration encompasses three procedures:

1. **Primary Calibration** - Determining the error of some system parameter with reference to a "gold standard".
2. **Operational Calibration** - Applying the error calculated during Primary Calibration to the measured values of system parameters during operation. This is necessary because the reference used for primary calibration usually cannot be accessed by the system on a continuous basis, or in a convenient manner.
3. **Calibration Verification** - Ensuring that the calibration has not drifted over time.

GLV

GLV has two subsystems that are acquiring data, GLV Power and Voltage from the TSV. These two systems will then report their respective data back to VSCADA. As the components for these subsystems have yet to be determined, only required accuracies can be determined as of this time. The process of calibration of components will be provided once the components have been selected.

Accuracy

GLV Power

Voltage - The voltage measured by GLV Power shall be accurate to within ±0.5 v of an independently verified measurement. This accuracy guarantees safe operation that should prevent potentially hazardous situations.

Current - The current measured by GLV Power shall be accurate to within 500 mA of an independently verified measurement. This accuracy guarantees safe operation that should prevent potentially hazardous situations.

State of Charge - The state of charge of the battery shall be accurate within 1% of total charge. This accuracy will provide for safe charge and discharge of the battery without the fear of causing a fire or meltdown of the pack.

Temperature - The temperature of the battery shall be accurate within 1 ℃ to ensure safe operation of the system at all times.

TSV Voltage

TSV voltage will be measured and the component(s) making the measurements will be accurate to within ±0.5v of the actual voltage. This accuracy should be independently verified and will provide for safe operation and testing.

Primary Calibration

Components should be selected such that they come calibrated within the tolerances outlined in the Accuracy subsection. If the component does not come pre-calibrated, a test should be devised and executed that demonstrates the sensor is accurate within the tolerances outlined in the Accuracy subsection.

Operational Calibration

Based on the data and known inaccuracies of the components primary calibration, develop a calibration plan to account for these inaccuracies if necessary. Quick measurements with an accurate measurement device can be made to ensure accuracy.

Calibration Verification

Components should be tested by measuring values alongside a known to be accurate device to ensure the accuracy of the components. Any errors should be noted and all data collected should be used in developing a calibration of the sensor if necessary.

Dynamometer

The sensors on the dynamometer system give feedback regarding the state of the motor and the motor controller. The sensors used by the dyno team will be proven and demonstrated to be accurate within reason for the scope of their use. The sensors will also be calibrated such that the VSCADA team will be able to account for any variance in sensor accuracy if any should exist. The Motor Controller System has five sensors that need calibrated. Those measurands are: torque, motor velocity, motor current, controller input voltage, and system temperature.

Primary Calibration

Torque

Completed by Omegadyne and is 5 point NIST traceable in tension at 0%, 50%, 100%, 50%, and 0%.

Motor Velocity

No primary calibration is necessary, either the product works or it doesn't. Verification of accuracy will be preformed in Operational Calibration.

Motor Current

No primary calibration is necessary. The sensor is in place in the motor controller and its specification is not given. Verification of accuracy will be performed in Operational Calibration.

Controller Input Voltage

No primary calibration needed. The sensor is provided with the motor controller and its specification is not given. Verification of accuracy will be performed in Operational Calibration.

System Temperature

Completed by NXP and is outlined in the datasheet for the part. The sensor is linear from with one slope from 0℃ to 100℃ and with another slope from 100℃ to 200℃. This data will be used to prove accurate calibration.

Operational Calibration

Torque

To calibrate the torque, first enter a "0" for A0, a "1" for A1, and 0's for the remaining A2-A4 (if applicable). This puts your readout in linear volts. Remove the drive shaft or belt and any calibration weights or bars that are not normally on the brake when running. Tap the brake and/or torque bar with your hand or a rubber mallet to remove any residual stiction in the system. Now observe your torque voltage (V1) and write it down. Next, hang the calibration weight(s) on your brake. Now, tap the brake to again remove any stiction in the system. Observe and write down the voltage reading (V2). Calculate your calibration torque by measuring the weight of the calibration weight assembly times the distance from the center of the pivot on the brake. This is your total foot pounds for the calibration. Now, divide the foot pounds by the difference in voltages and enter this number in A1.

calibration weight: 105.8 lbs.
lever distance to calibration weight : 36"/12 = 3'
V1 = .56 volts V2 = 6.24 volts
calibration weight torque = 105.8 X 3 = 317.4 ft-lb
A1= 317.4/(6.24-0.56) = 55.88 ft-lb/volt

Enter this value into A1. Now enter a value into A0 that makes the system read 317.4 ft.lb. (example only). Example: If after you enter 55.88 into A1 the reading goes to 348.7, enter a value of 317.4 - 348.7 = -31.3. The actual number may be more like -250. You can adjust this number up or down until the reading is 317.4 (example only). Your numbers will vary from this example.

Your torque should now be calibrated. You may remove the calibration weights and check the zero value. This number may be a little off but do not adjust it to zero. Remember, it is more important that the number be right on at the nominal torque than to read zero. No motor has zero torque.

Motor Velocity

Calibration will be performed by spinning the gear inside the dynamometer a known number of revolutions and comparing the number of teeth counted by the encoder versus the known number of teeth on the gear multiplied by the number of revolutions. Corrections can be made using the software provided by Huff.

Motor Current

Since a known amount of current can be supplied by the Magna Power TS Series IV comparing the current provided to the current read by the motor controller can be achieved reliably through software. A fix can then be noted and an appropriate remedy to the amount of current at the motor controller can be made knowing that the power supply is accurate to ± 0.075% of full scale current. This metric was provided by Magna Power. As long as the current measured by the motor controller is within ± 0.075% of the current provided by the power supply no correction is needed.

Controller Input Voltage

The controller input voltage can be calibrated in the same manner as the motor current. A known amount of voltage can be supplied from the Magna Power power supply. Comparing the value read by the Curtis motor controller and the value provided by the motor controller, a quick analysis of accuracy can be made. The power supply is accurate within ± 0.075% of full scale voltage. As long as the value read by the motor controller is within that range no further calibration is necessary. However if the values vary outside of that range a new range of accuracy must be developed for the motor controller based off the worst case scenario for the supplied voltage and the voltage read by the motor controller. With the accuracy of the voltage sensor determined, a new range of input voltage can be determined for the motor controller and verified from another power source.

System Temperature

Operational calibration should be minimal as the sensor should be working within the range of accuracies provided by the data sheet from the manufacturer. Corrections to the measured value can be applied based on the predictions of the known accuracies of the temperature sensor provided by the data sheet from NXP.

Calibration Verification

Torque

Verification of calibration accuracy will be performed during the ATP tests. These tests, outlined in D004, cover the full range of expected values from the system and any error will be noted and corrected during testing.

Motor Velocity

Verification of calibration accuracy will be performed during the ATP tests. These tests, outlined in D004, cover the full range of expected values from the system and any error will be noted and corrected during testing.

Motor Current

Verification of calibration accuracy will be performed during the ATP tests. These tests, outlined in D004, cover the full range of expected values from the system and any error will be noted and corrected during testing.

Controller Input Voltage

Verification of calibration accuracy will be performed during the ATP tests. These tests, outlined in D004, cover the full range of expected values from the system and any error will be noted and corrected during testing.

System Temperature

Verification of calibration accuracy will be performed during the ATP tests. These tests, outlined in D004, cover the full range of expected values from the system and any error will be noted and corrected during testing.

TSV

This section is a revision of the LFEV-ESCM-2014 document.

System Specifications

The various LFEV-ESCM system measurands serve different purposes. Some must be measured with higher accuracy than others. The following table outlines the target accuracy of the various system measurands.

Parameter	Accuracy ±	Units
Cell Voltage	5	mVDC
Pack Voltage	0.1	VDC
Pack Current	1.0	A
Cell Temperature	5	℃
Shunt Temperature	2	℃
Fuse Temperature	5	℃

Cell voltage requires a higher accuracy than pack voltage. The cell voltage is used to make decisions about the safety of the system and about cell balancing. As the cells are sensitive to voltage levels, particularly at the extreme ends of the operational SOC range, it is important to measure the cell voltage accurately.

Pack voltage is a convenience measurement. It is not used to calculate any other system parameters.

Cell temperature is a safety measurement. It is not reasonable to say that a cell at 64.999°C steady-state is “safe”, while a cell at 65.001°C steady-state is “unsafe”. Therefore we are not interested in the exact temperature of the cell, only the trend of the measurement. The ±5°C tolerance is sufficient to establish this trend.

Fuse temperature is a convenience measurement. It is not used to calculate any other system parameters.

Shunt temperature is used to calibrate the current measurement. The resistivity of the shunt changes with temperature and must be corrected to obtain an accurate current reading. The accuracy of the sensor is ±2°C according to the datasheet.

System Calibration

Cell Voltage

Primary calibration of voltage measurements is performed using an Agilent lab supply and multimeter to obtain error coefficients for the measured values.

To calibrate an AMS board, follow these steps:

1. Connect the banana jacks on the AMS board to the 0-6VDC output of the lab supply using test leads.
2. Connect the multimeter to the banana jacks on the AMS board.
3. Connect the board's I2C interface to a PC running RealTerm using the I2C to USB adapter.
4. The boost voltage regulator on the AMS board will operate when 1 to 6 VDC is present at the banana jacks. In 0.5V increments, test the entire operating range of the AMS board. For each of the voltage settings, record the multimeter reading, and the value reported by the I2C voltage query command.
5. Plot the measured values (y-axis) against the AMS reported values (x-axis). The resultant offset β and slope α of the best-fit equation indicate the error transfer function of the voltage measurement circuit.
6. Record these β and α parameters for each cell in the configuration file.

Table 1. Example AMS Cell Voltage Calibration Chart

Voltage	Multimeter Reading	AMS I2C Reading	Error (V_{meter} - V_{I2C})
1.0			
1.5			
2.0			
...	...	...	...
5.5			
6.0			

Pack Voltage

The total pack voltage is not used to perform any calculation or trigger any state transition, and therefore does not need to be measured with the same level of precision as the individual cell voltage measurements. When no load current exists, the pack voltage should ideally be equal to the sum of the cell voltages.

To calibrate the pack voltage measurement, follow these steps:

1. The TS-8160-4200 power connection and PacMan BoB power connection connection must be accessible. Connect both the TS computer and the PacMan BoB inputs to the +25VDC output of the lab supply.
2. Connect the multimeter to the PacMan BoB power connection
3. The TS-8160-4200 operates from 5-28 VDC. In 1V increments, test the 5-25V operational range. For each of the voltage settings, record the multimeter reading, and the value reported on the LCD display.
4. Plot the measured values (y-axis) against the PacMan reported values (x-axis). The resultant offset β and slope α of the best-fit equation indicate the error transfer function of the voltage measurement circuit.
5. Record these β and α parameters in the configuration file.

Table 2. Example PacMan Voltage Calibration Chart

Voltage	Multimeter Reading	PacMan Reading	Error ($V_{meter} - V_{PacMan}$)
5.0			
6.0			
...	...	...	...
24.0			
25.0			

Temperature

For safety reasons, the temperature of accumulator cells must be monitored (EV3.6.3, EV3.6.6). We are not using the reported temperature value in any further numerical calculations, but only as an "on-off" switch to protect the user and the system from dangerous fault conditions. In order to perform a full-range temperature calibration, we would need such equipment to hold the entire device at specific temperatures for measurement. However, we must also consider that the AMS temperature sensor is not immersed in the cell, or even directly attached to the outer casing. 2013 analysis has calculated a relation between the temperature of the cell and the temperature of the sensor. This should be considered when setting the temperature limits in the configuration file.

Current

Measuring current is important for determining system SOC. Our system is designed for a maximum current of 600A. The IC we are using to measure current (LTC4151) has a resolution 12 bits at 20μV/bit, with a saturation limit of 81.92mV. Therefore the theoretical maximum resolution we can obtain is 600A/212, or 0.146A/bit. We have designed the shunt resistor with a resistance on the order of 120µΩ, to give a maximum shunt voltage of 71mV at 600A. This allows some headroom on the sensor input.

When the AIRs are open, the only current draw on the system is due to internal components. This value is expected to be relatively constant, but cannot be reliably measured by the current sensor because it is on the same order of magnitude as the sensor's bit resolution. Therefore the total current draw of the internal components (the parasitic load) should be estimated empirically using a lab supply.

To calibrate this "open-AIR" current draw, the power supply inputs of the PacMan computer and breakout board should be connected in series with a multimeter to the +25VDC output of a lab supply. Set the multimeter to measure current and set the power supply to 24VDC. Record the current reading reported by the multimeter in the configuration file. This value is the parasitic load on the pack.

To calibrate the high-current measurement, the resistance of the shunt must be known. A four-wire measurement technique is used to obtain this value. Connect the shunt in series with a multimeter to the 0-6VDC output of a lab supply using alligator clip test leads. Set this multimeter to measure DC current. Connect a second multimeter at the two tapped holes designated as current measurement points. Set this multimeter to measure DC voltage.

Set the current limit of the lab supply to 2.5A and turn it on. Record the actual current as reported by the first multimeter, and the shunt voltage as reported by the second multimeter. Using Ohm's law, find the resistance of the shunt. The value should be on the order of 120µΩ. Record this resistance value in the configuration file.

Additionally, in past years it has been found that significant heating of the shunt occurs when the pack is being charged at high current values. This changes the resistance of the shunt, thereby skewing our current measurement. A temperature sensor will be mounted onto the shunt to monitor temperature which will then be used to calculate a new effective resistance for the current measurement.

State of Charge

The system State of Charge (SOC) is calculated by integrating the current flow in the pack over time (coulomb counting). This mathematical integration inherently contains two possible sources of error: the integration constant "C" which defines the initial conditions, and drift caused by uncompensated accumulation of error over time. To resolve these unknowns, we use a voltage threshold at the extreme ends of the SOC range to correct any drift. Each time the pack voltage reaches the upper limit during charging, the SOC is reset to 100%. Each time the pack voltage reaches the lower limit during discharging, the SOC is reset to 0%.

This method has been shown in the past to be ineffective, mainly due to heating-related current measurement problems, and code which did not preserve state of charge when the computer was reset. These will be fixed in our new design. Additionally a new technique for measuring SOC is currently being researched by one of our team members.

Confidence Interval

As stated in the LFEV-Y2-2014 spec, "Numerical specifications shall be considered "passed" if the measured value is demonstrated by empirical statistical trials to meet the specification at a 90% confidence interval." Confidence interval is calculated by a straightforward formula from statistics:

$$confidence\ interval\ bounds = \bar{x} \pm t * s_m \qquad \text{EQ. 1}$$

where $\bar{x}$ is the sample mean, s_m is the standard error, and t is a value which represents the allowable number of standard deviations for a given sample size. In our system, the sample size varies based on the system parameter being measured.

Table 3. Number of Measurements Made by the System

Parameter	No. of measurements made
Cell Voltage	7
Cell Temperature	7
Pack Voltage	1
Pack Current	1
AIR Temperature	1
Fuse Temperature	1
Shunt Temperature	1

When considering a small sample size, it is more appropriate to use the t-distribution than the normal distribution in confidence interval calculations. The t-distribution assumes more values in the tails of the graph than the normal distribution does for small sample sizes.

Table 4. t-distribution Coefficients for 90% Confidence Level

Sample Size	t (standard deviations from mean
1	6.314
5	2.015
7	1.895
10	1.812

For the cell voltage measurement, calculate the confidence interval using the following steps:

1. Aggregate the voltage data for 3.0VDC for all seven AMS boards.
2. Calculate the mean and standard error of the data set.

3. Calculate the confidence interval using EQ. 1 specified above with a t value corresponding to a sample size of 7.

For the cell temperature measurement, calculate the confidence interval using the following steps:

1. Aggregate the temperature data for all seven AMS boards.
2. Calculate the mean and standard error of the data set.
3. Calculate the confidence interval using EQ. 1 specified above with a t value corresponding to a sample size of 7.

Clearly those measurements with a sample size of 1 will not give meaningful results about the accuracy of the system. Since we do not have multiple systems to collect data regarding the pack-level parameters, we can use multiple values over a small range measured by the same system to generate a sample space.

For the pack voltage measurement, calculate the confidence interval using the following steps:

1. Set up the PacMan for primary calibration. See the section labeled "Primary Calibration - Pack Voltage" for details.
2. In 0.2V increments, test the 22.0-23.8VDC operating range. For each of the voltage settings, record the multimeter reading, and the value reported on the LCD display. Calculate the difference in the multimeter and PacMan-reported values.
3. Calculate the mean and standard error of the data set.
4. Calculate the confidence interval using EQ. 1 specified above with a t value corresponding to a sample size of 10.

Table 5. Example 90% Confidence Level Pack Voltage Calibration Chart

Voltage	Multimeter Reading	PacMan Reading	Error ($V_{meter} - V_{PacMan}$)
5.0			
6.0			
...	...	...	...
24.0			
25.0			

Table 6. Calculated Confidence Intervals for System Measurands

Parameter	Confidence Interval
Cell Voltage	
Cell Temperature	

Pack Voltage	
Pack Current	
AIR Temperature	
Fuse Temperature	

Operation Calibration

During operation, the system uses the primary calibration constants to provide a better estimate of the true value of the system measurands. The following sections describe how each measurement is corrected using calibration coefficients.

Cell Voltage

During operation, the PacMan will correct the pack voltage returned from the AMS by applying the following equation:Vactual=*Vmeas+. The value β compensates for any bias in the circuit, such as op-amp input bias. The value α compensates for any linear error, such as mismatched resistor values.

Pack Voltage

During operation, the PacMan will correct the pack voltage returned from the LTC4151 by applying the following equation:Vactual=*Vmeas+. The value β compensates for any bias in the circuit, such as op-amp input bias. The value α compensates for any linear error, such as mismatched resistor values.

Temperature

Current

Calibration Verification

Pack Voltage

Pack voltage measurement can be verified by following this procedure:

1. Connect the charger and set the current limit to 1 amp.
2. Record the voltage at the charger displayed on the charger.
3. Connect the pack to a PC using the CAN interface.
4. Using RealTerm, obtain the pack voltage as reported by PacMan. Record this value.
5. The difference in the measured and reported values should be within the 90% confidence interval specified in Table 6.

Table 7. Pack Voltage Calibration Verification Chart

PacMan Voltage	**Charger Voltage**	**Error (V_{meter} - V_{PacMan})**

Cell Voltage

Cell voltage measurement can be verified by following this procedure:

1. Connect the pack to a PC using the CAN interface.
2. Using Realterm, obtain the pack voltage as reported by PacMan.
3. Using Realterm, obtain each of the seven cell voltages as reported by PacMan.
4. Sum the cell voltages. The difference in this sum and the reported pack voltage should be within the 90% confidence interval specified in Table 6.

Table 8. Cell Voltage Calibration Verification Chart

PacMan Voltage	Sum of Cell Voltages	Error (V_{meter} - V_{PacMan})

Temperature

Temperature measurement can be verified by following this procedure:

1. The pack must be at a "rest" state. This means that no charge or discharge has occurred for at least 6 hours prior to verification.
2. Obtain and record the ambient temperature. This would be easiest to do indoors, where the ambient temperature is somewhat predictable.
3. Connect the pack to a PC using the CAN interface.
4. Using RealTerm, obtain temperature measurements of one cell and the discharge fuse.
5. The difference in temperature reported and the ambient temperature for both components should be within the 90% confidence interval specified in Table 6.

Table 9. Temperature Calibration Verification Chart

Component	Component Temp	Ambient Temp	Error (V_{comp} - V_{amb})
Fuse			
Cell			

Current

Current measurement can be verified by the following procedure:

1. With the pack in a "rest" state, read the current displayed on the LCD. The current should display "0A".
2. Connect the charger to the pack.
3. When the pack begins charging, record the current on the charger front panel.
4. Record the current displayed on the LCD panel.

5. The difference in current reported by the pack and the current displayed on the charger should be within the 90% confidence interval specified in Table 6.

Table 10. Current Calibration Verification Chart

PacMan Voltage	Charger Voltage	Error (V_{meter} - V_{PacMan})

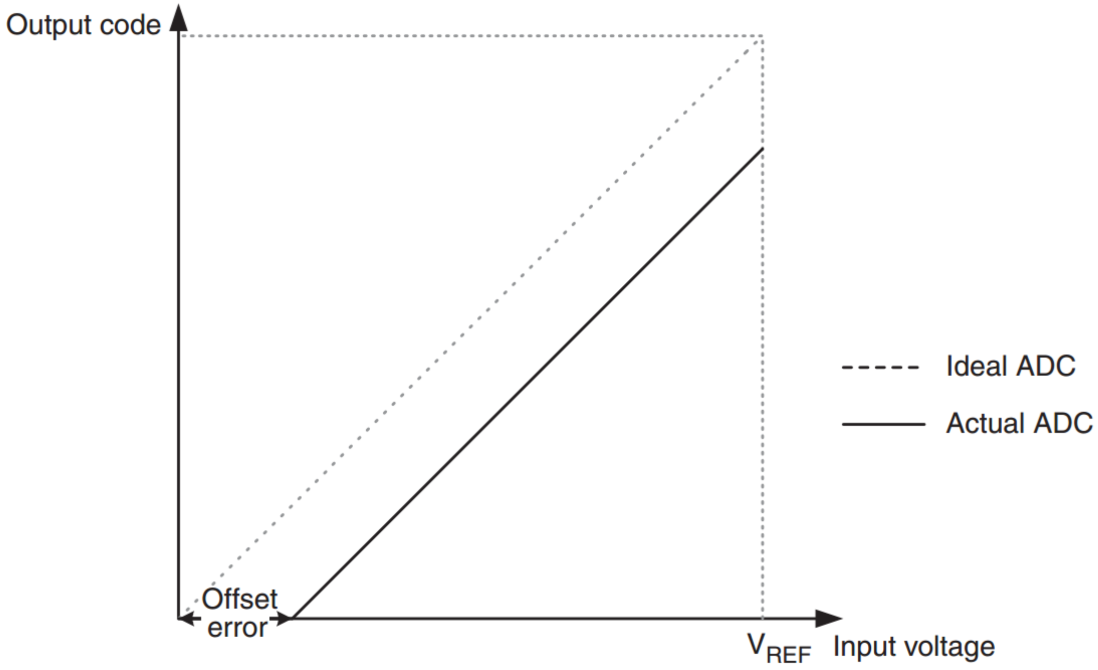
VSCADA

VSCADA computer acquires data from other vehicle systems through CAN bus. This protocol will be capable of sending and receiving basic sensor data. Once digital data arrives on the VSCADA computer, a configuration file, unique to the transmitting sensor, will specify the interpretation of the raw data. Each sensor configuration file will be written by the VSCADA team, with the help of the relevant team.These modular sensor configuration files will describe how raw sensor data is converted into linearized unit of measurement. The configuration files need to be created or updated when new sensors are added. Since all digital sensor data will be proven accurate and calibrated by the group responsible for its collection, the only data acquisition VSCADA is concerned with is the analog to digital conversion.

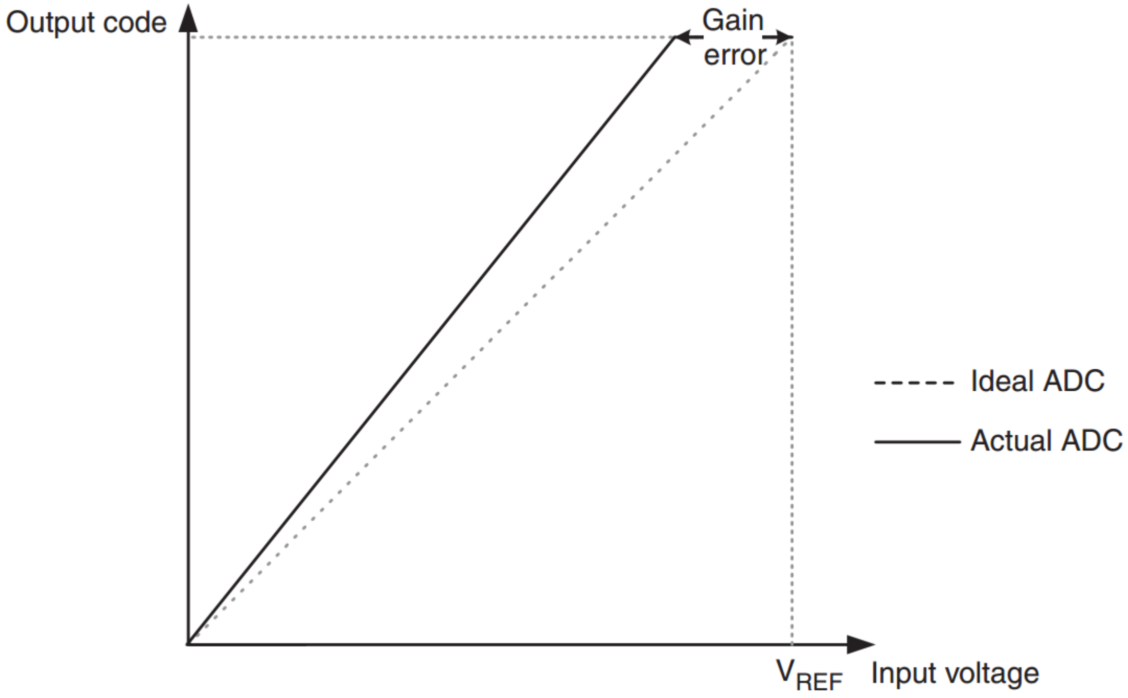
Accuracy

There might be inaccuracies in the ADC of the ATMEGA 16M1 micro-controller, as suggested in its datasheet. The inaccuracies include: offset, gain errors, nonlinearities and quantization error. The value of the quantization error is always contained within ±0.5LSB, and ideally, the values of other inaccuracies are 0 LSB. The values of these other inaccuracies, like offset and gain, needs to be measured and calibrated.

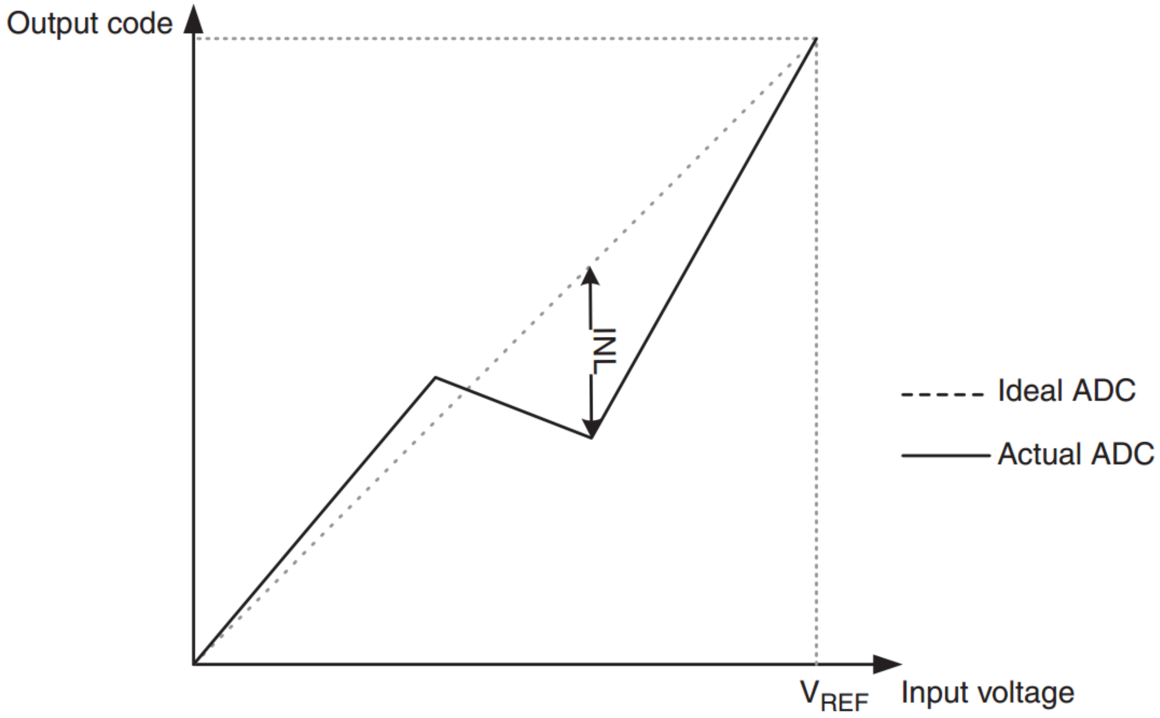
1. Offset:
The deviation of the first transition (0x000 to 0x001) compared to the ideal transition (at 0.5 LSB). Ideal value: 0 LSB



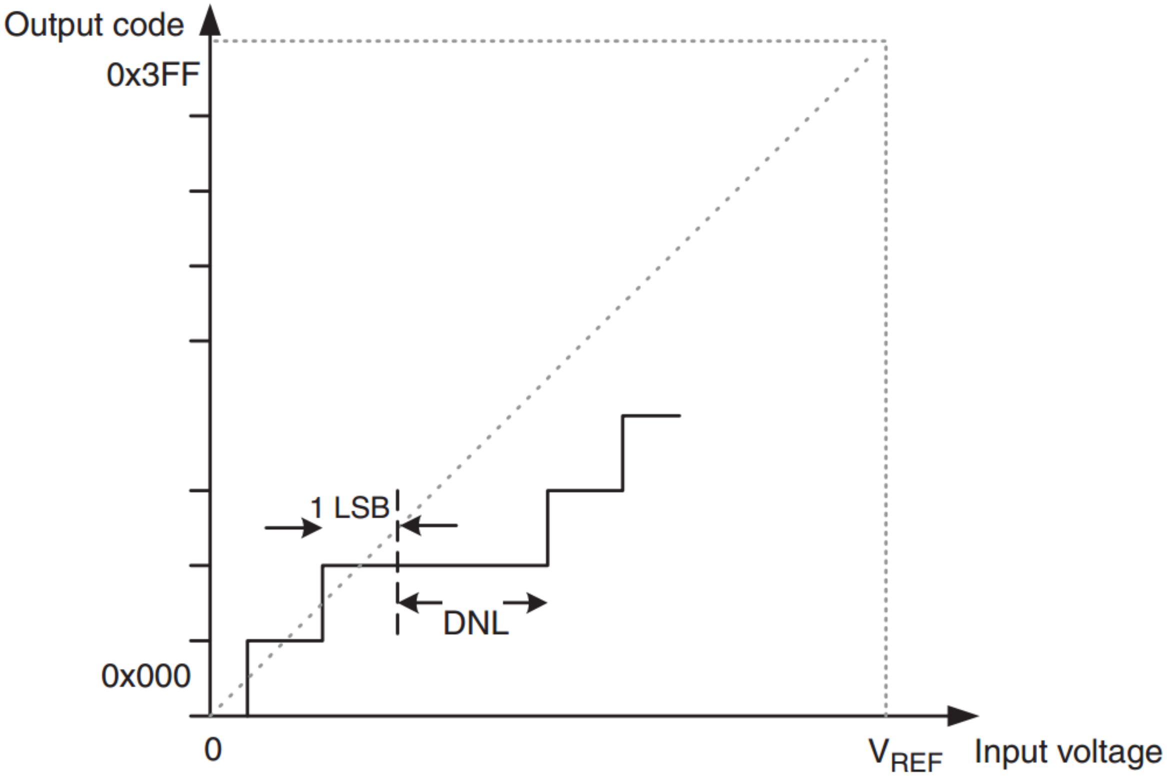
2. Gain Error:
After adjusting for offset, the Gain Error is found as the deviation of the last transition (0x3FE to 0x3FF) compared to the ideal transition (at 1.5 LSB below maximum). Ideal value: 0 LSB



3. Integral Non-linearity (INL):
After adjusting for offset and gain error, the INL is the maximum deviation of an actual transition compared to an ideal transition for any code. Ideal value: 0 LSB



4. Differential non-linearity (DNL):
The maximum deviation of the actual code width (the interval between two adjacent transitions) from the ideal code width (1 LSB). Ideal value: 0 LSB



5. Quantization Error:
Due to the quantization of the input voltage into a finite number of codes, a range of input voltages (1LSB wide) will code to the same value. Always ±0.5LSB

6. Absolute Accuracy:
The maximum deviation of an actual (unadjusted) transition compared to an ideal transition for any code. This is the compound effect of offset, gain error, differential error, non-linearity, and quantization error. Ideal value: ±0.5LSB.

Primary Calibration

Primary calibration was achieved by the manufacturer and is outlined in the datasheet on page 225 section 21.8.2.

Operational Calibration

Operational calibration is outlined in the datasheet for the chip. The calibration requires that a calibration value is measured and stored in register or EEPROM. The calibration can be performed by utilizing the formula: $T = \{[(ADCH << 8 \mid ADCL] - T_{OS}\}/k$ where ADCH and ADCL are the ADC data registers, k is a fixed coefficient and T_{os} is the temperature sensor offset value determined and stored into EEPROM.

Calibration Verification

Verification will be achieved using analysis based on the results from Operational Calibration and testing. The calculations and/or demonstrations will show accurate results within the range of accepted values.