System Calibration and Error Analysis

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Abstract

This document details the calibration of system measurands in the 2014 LFEV-ESCM. Both measurand accuracy and calibration methods are detailed.

Table of Contents

Introduction

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 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.

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	°C
Shunt Temperature	2	°C
Fuse Temperature	5	°C

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/2^{12}, 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.

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%.

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:

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

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	2
Fuse 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 ($V_{meter} – V_{PacMan}$)
22.0			
22.2			
…	…	…	…
23.6			
23.8			

Table 6. Calculated Confidence Intervals for System Measurands

Parameter	Confidence Interval
Cell Voltage	
Cell Temperature	
Pack Voltage	
Pack Current	
AIR Temperature	
Fuse Temperature	

Operational 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=$_{*\mathrm{Vmeas}+}$. 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=$_{*\mathrm{Vmeas}+}$. 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 RS-485 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 RS-485 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 ($V_{sum} - V_{PacMan}$)

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 RS-485 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 Current	Charger Current	Error ($V_{charger} – V_{PacMan}$)