Test Temperature Calibration Using Inertial MEMS Voltage-Temperature Characteristics for ATE Setup

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***Abstract*—In the chip-scale package final test, temperature is one of the main components as this is also indicated on once specification on electrical parameters that are temperature sensitive especially for inertial Micro-Electro-Mechanical Systems (MEMS) accelerometers. The voltage-temperature relationship of an accelerometer has been presented and used to calibrate test temperature on Automated Test Equipment (ATE) setup. Bench reference data of a set of units were gathered to correlate with the Device under Test (DUT) temperature with the raw ATE handler test temperature using linear regression. Offset test temperature or the temperature error was calculated across all sites to adjust the new ATE handler test temperature. After which, the correlation between the bench reference data and the gathered ATE data of the 20 golden units from two test flows with 2.3 seconds and 200 milliseconds respectively both with 4-site enabled testing was validated that all DUT temperature is within acceptable temperature window of +/- 3°C, also less standard deviation for longer test time by only 0.0011 and all 20 golden units passed for both test flows. Lastly, the comparison of the newly calibrated test handler using the voltage-temperature relationship which had 0.0011, 0.0011, and 0.0012 SD of data, and the static calibrated test handlers which had 0.0057, 0.0078, and 0.010 SD of data for each lot 1, 2, and 3 respectively show up to 8x improvement in SD of the DUT temperature in ATE.**

***Index Terms*—MEMS, ATE, voltage, temperature, offset, thermal error, linear regression analysis**

I. Introduction

Micro-Electro-Mechanical Systems (MEMS) accelerometers are results from advanced studies and procedures of microfabrication and they can also be described as a combination of a mechanical and electrical system of components [1]. Manufacturers of MEMS devices depend on the structure of the device on the product application and its product requirements. Most MEMS products particularly accelerometers are implemented through multi-chip integration where the MEMS and IC (integrated circuit) are being designed, manufactured, and tested separately. It is them assembled and ultimately developed into a multi-chip system. Through the years, there are multiple solutions for a multi-chip system and to name some are the system-in-package solution and chip-scale package [2]. Fig. 1 shows an overview of how a chip scale package looks like. By having this complex structure, before a device be released to the market, it must undergo critical and strategic processes that are expected to cost high thus, many researchers pursue the parallelism capability of this process to lower the cost [3], [4]. These processes and acts as key engineering disciplines can be categorized into three: 1) design activity wherein simpler words take an IC's specification and convert it into a high-level and working circuit, 2) fabrication where it translates the design into physical material, and test to ensure that the fabricated IC is working without faults [5]. As important of all the processes, the final test is one of the final touches of an IC's manufacturer to record and establish the functionality of a device where the device is calibrated and trimmed commonly using a combination of 1) Automated Test Equipment (ATE) which is a collection of high-level electronic systems for testing requirements, 2) IC test handlers or the precision robotic electro-mechanical equipment and 3) optional with or without a stimulus module to induce physical motion [6]. Temperature is one of the main components during the final test as this is also indicated on once specification especially on electrical parameters that are temperature sensitive [7].

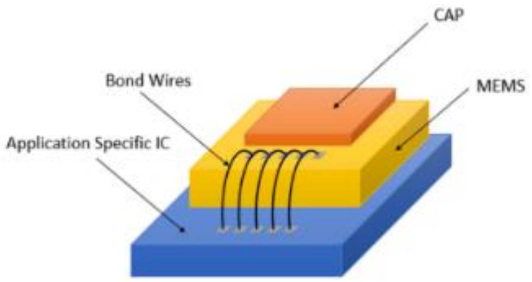

Figure 1. MEMS chip scale package.

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As there are many factors during ATE testing that may cause a shift of temperature being detected by the main package cavity of the IC such as the IC test handler's temp sensor calibration method on different setups and mechanical failures of the equipment as well. The drawback of these variations will result in differences in multiple aspects of the hardware's performance which is a vital contributor which would lead the ICs experience power and temperature shifts. From a previous study, this means that the thermal aspects of hardware testing must be revised or fixed. The difference between the IC test handler's temperature and the actual temperature is called temperature error [8]. As experienced on some ATE testing that uses a test handler as its temperature source shown in Fig. 2 is a sample of readings from an accelerometer being tested with seen shift on temperature based on the diode voltage measure within the device which is temperature-sensitive. This indicates that the temperature per DUT is different where in this case, devices' temperature varies per site. Fig. 3 then shows the simplified functional diagram of the accelerometer. A series of commands to manipulate the test requirements is needed to enable the functionality of the diode voltage to be measured.

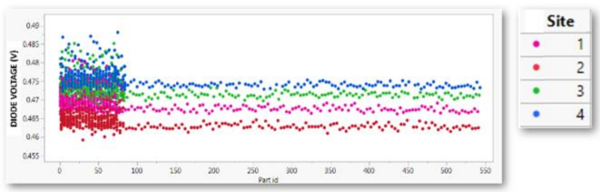


Figure 2. Sample data with observable shift of temperature sensitive parameter.

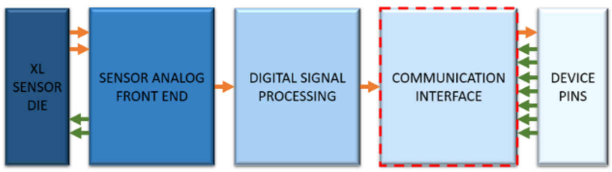


Figure 3. Simplified diagram of the accelerometer.

Due to this, there is an attempt to control the temperature for MEMS testing. A recent study used a silicon resonant accelerometer by adding temperature and frequency resonators by solving this error to the design structure of the device. They have successfully reduced the hysteresis error by 1/10 using the new method. The study presented data from -40C to 60C with the implemented solution for the temperature error. As discussed above, a MEMS IC undergoes multiple qualifications and testing at a range of temperatures depending on their applications. Some inertial MEMS for automotive applications are being tested up to 125C since temperature plays a critical role in all of the MEMS processes [9]. Another related literature is also research that presented the first CMOS MEMS thermo-electronic multi-directional flow sensor which includes a constant temperature circuit based on diode thermal feedback and then being used to calibrate the sensor [10]. Observed gaps from the previous studies are that the presented data extends from -40C to 60C with the implemented solution for the temperature error. Automotive accelerometers are tested at a wider range. Most of the proposed solutions are only applicable to those that are on a design stage evaluation.

This paper will aim to study an inertial MEMS accelerometer using its voltage-temperature characteristics to calibrate temperature during the final test setup. Through this goal, the study will need to develop a new strategy of test temperature calibration using inertial MEMS voltage-temperature characteristics for ATE setup by 1) characterizing voltage to temperature relationship on an ATE setup at all available slots, 2) create an algorithm from all gathered data and complete implementation at all characterized slots, 3) correlate gathered ATE data to the bench setup data to make sure temperature during testing is within the acceptable range.

The study will mainly increase the quality of testing during the final test and decrease the possibility of devices trimmed and calibrated at its exceeding temperature capability. It will develop a calibration method that can be applicable for a specific MEMS test setup with a stimulus module that is faster than the current calibration procedure being implemented.

The research will be focused on the inertial MEMS accelerometer specifically a high-gee single-axis accelerometer and its voltage behavior with temperature. The test setup using an automated Pick and Place handler, which is used for high volume testing and temperature control, will be utilized for data collection to represent the main setup of the device while a separate evaluation board with an external temperature source will be used for correlation purposes. The study will not involve a change in the design structure of the specified accelerometer. Furthermore, the study will not include and propose a change in the ATE and bench setup and over-all function.

II. Review of Related Literature

A. *Related Literature*

All There are two main ways to make temperature measurement very accurate and precise, one is to reduce noise or sudden shifts on temperature control and the other is to lessen thermal resistance from the temperature sensor to the chip being subjected to the actual test. Proposed additional temperature measurement resonators on the Silicon Resonant Accelerometer (SRA) to increase accuracy on temperature compensation [11]. Another study also proposed a new silicon resonant accelerometer to enable the release of stress due to the difference of temperature between the silicon and substrate which are all inside the chip. The method used was the characteristics of structural resistance already developed inside the structure. Measuring the resistance as the temperature is gradually being increased and then procuring the set point once the desired and actual resistance is attained [12].

Meanwhile, Reference [10] designed a constant temperature system with the sensitive element, the temperature of which is relatively stable but thermal power has increased, heat distribution in uneven and direct heating leads to a larger temperature gradient on the resonator.

Some use the quality factor and its effect in the temperature of the resonator to measure the device's temperature but due to its sensitivity to the circuit parameters, the compensation result is not too reliable [13].

Reference [14] proposed to improve the temperature stability of MEMS resonators using a constant-structural-resistance control where the Temperature Coefficient of Resistivity (TCR) of the MEMS resonator acts as an intrinsic temperature sensor giving a constant structural temperature. The problem to solve by the study may be different from this study however, the method to aim the objective is quite similar, improve temperature stability.

B. Related Literature

Linear regression is used to indicate the relation of the variables. Through regression analysis is used to predict and calculate the relationship of a certain variable against other variables. It is a modeling technique that is more accurate because it involves getting the rate of change of a dependent variable against the independent one [15], [16].

III. Research Methodology

A. Conceptual Framework

Fig. 4 below shows the conceptual framework used in the study. It is an input-process-output model where the input includes the preparation, gathering, and measurement of the golden units and its bench reference data into the repository. These inputs were then processed to be tested across the variety of sites and then used the new set of data to compare, analyze, and calculate using linear regression. Lastly, the output of the study is the accurate offset temperature of the test handler and the DUT temperature.

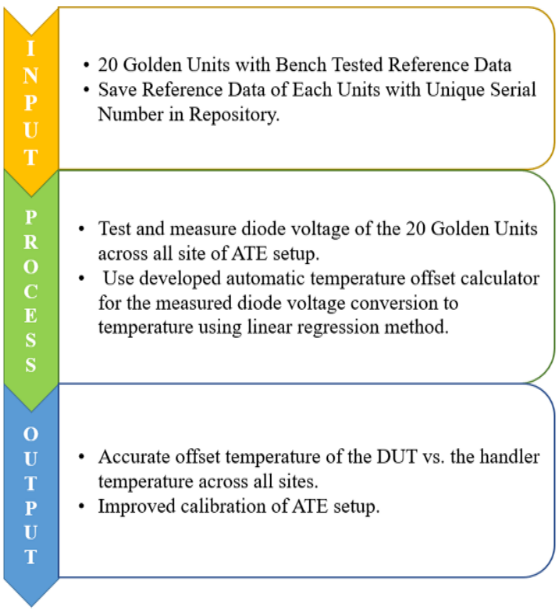


Figure 4. Conceptual framework (I-P-O).

B. Evaluation of Setups and Process

1) Bench setup

The diode voltage of the 20 golden units is measured in the bench setup where the only difference from an ATE setup is that the control of the handler will not be used. LabView 2013 is used to perform bench testing. To set the temperature, a calibrated thermal chamber is used.

A bench evaluation board is used which has the same function as with the ATE boards. After evaluating the board by running different multiple tests to make sure the board is functional, the thermal chamber was set up beside the evaluation board. The units are then tested at temperatures -40°C, 25°C and 125°C with a soak time of 120 seconds before each measurement. These temperatures are the recommended test temperature for the device.

2) ATE setup

All boards are used in the ATE testing has been developed and being used by the device for functionality checks. Two types of boards used for this setup are 1) a performance board that is placed on the tester to connect with the resources, 2) a plunged board which is installed set up to the handler, and connect to the performance board via SAMTEC cables. The test has been developed using the software LabView 2013 and Test Stand 2013 to cooperate with the NI STS tester. Delta Matrix Handler is used as this is currently available and needs to be evaluated.

Test code is developed to automatically measure the diode voltage of the DUT, read the serial number to parallel check it has been bench tested and has reference data, and save the measured data. The 20 golden units were then tested at the specific temperatures and measured its diode voltage.

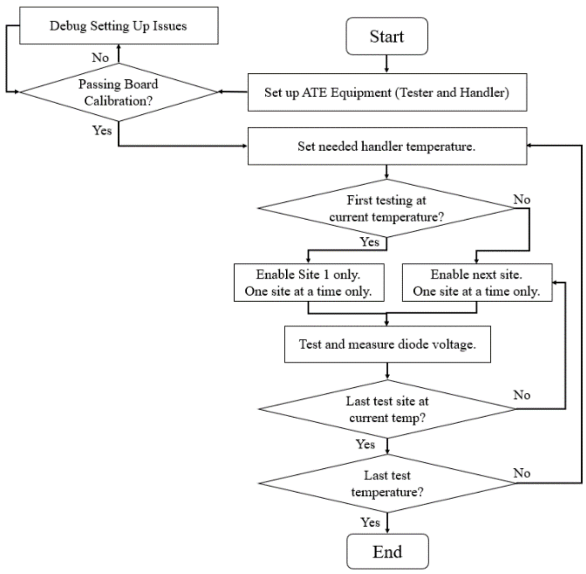


Figure 5. Flow chart of the ATE data gathering.

Figu. 5 shows the flow of how the ATE data gathering was performed by the researcher. The temperature was set to (Temp Read 1) target temperature - 10°C, (Temp Read 2) target temperature, and last at (Temp Read 3) target temperature + 10°C.

IV. Result and Discussions

A. Data Gathering

1) Bench setup

Table I shows the gathered data of the 20 golden units. The values of each serialized devices are saved in a restricted repository for the ATE setup's data gathering reference.

TABLE I. Bench Reference Data

Serial Number	Diode Voltage Measurement (V)		
	-40C	25C	125C
1	0.7901	0.6561	0.4515
2	0.7870	0.6550	0.4649
3	0.7560	0.6439	0.4428
4	0.7820	0.6582	0.4722
5	0.7885	0.6566	0.4657
6	0.7753	0.6555	0.4726
7	0.7695	0.6602	0.4627
8	0.7703	0.6578	0.4680
9	0.7711	0.6583	0.4641
10	0.7708	0.6563	0.4719
11	0.7699	0.6577	0.4645
12	0.7709	0.6558	0.4590
13	0.7716	0.6553	0.4532
14	0.7698	0.6554	0.4596
15	0.7704	0.6572	0.4634
16	0.7711	0.6581	0.4676
17	0.7694	0.6570	0.4721
18	0.7702	0.6579	0.4581
19	0.7710	0.6584	0.4688
20	0.7707	0.6564	0.4706

Fig. 6 below displays the user interface on how the data is being saved. SN0 to SN5 corresponds to the register fields that are unique per device and in this sample, it corresponds to the Serial Number 1 shown in Table I.

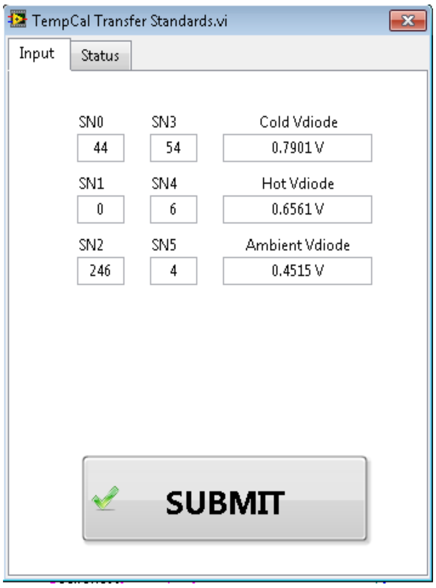


Figure 6. UI for submitting bench reference data.

Fig. 7 shows the measured diode voltage against temperature. By analyzing the data, the calculated average R-squared of all the data sets is 0.999 and the average calculated temperature coefficient is -1.88mV/°C.

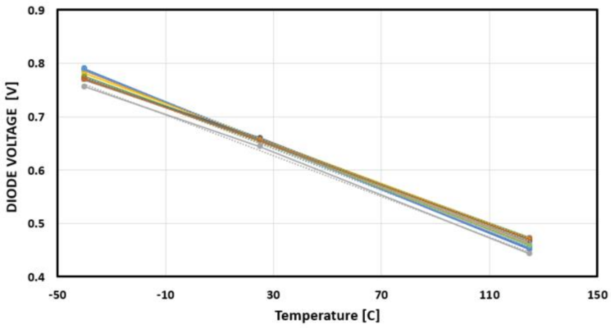


Figure 7. Plotted bench reference data (diode voltage vs. TEMPERATURE).

2) ATE setup

Data logging the current handler temperature can be performed in two ways, the researcher created an option for a manual and automatic read of the handler. In this study, manual user input of handler temperature has been used. See Fig. 8.

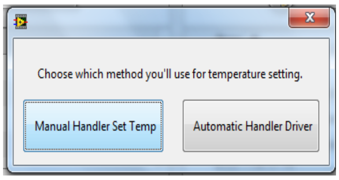


Figure 8. Created options for handler temperature data logging.

Fig. 9 then shows the front panel once the manual setting is selected. Diode voltage measurement will then be measured after handler temp is within the test window which is +/- 3°C. A pop-out error will occur when the input temperature is not within the acceptable window.

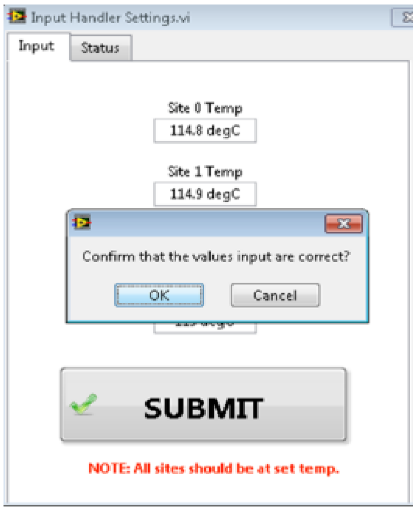


Figure 9. Handler temperature input for manual handler setting.

Collectively, three temperature reads and three diode voltage reads per test temperature was data logged.

B. Offset Algorithm

Below in Fig. 10 shows the corresponding graph of ATE data on each site where the diode voltage is now the dependent variable and its corresponding linear equation in slope-intercept form and its R-squared value which are all approximately equal to 1.

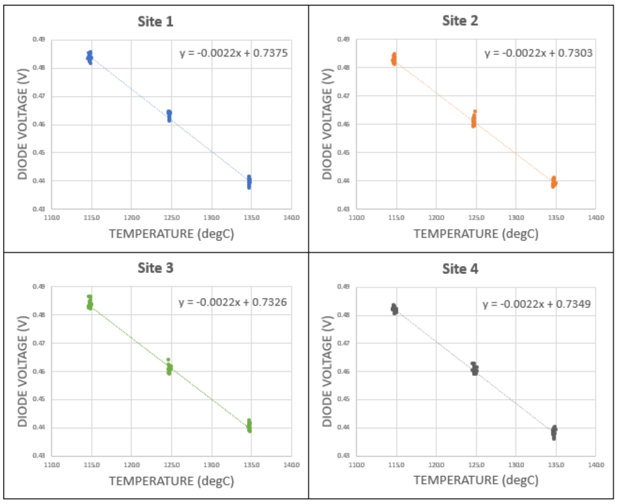


Figure 10. Graphical presentation of the ATE gathered data across all sites.

The researcher developed an algorithm for automatic offset temperature calculation after all data collection of diode voltage is gathered. It has been incorporated and developed into a new method for the software program.

Fig. 11 below shows a snippet of the actual LabView developed code for the automatic calculation of the offset.

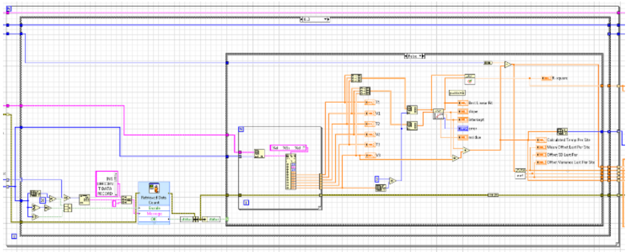


Figure 11. A snippet of LabView code developed for auto-calculation of temperature offset.

All diode voltage and corresponding handler test temperature gathered were pulled from the repository across all sites and used to Equation (1) where Y is the diode voltage reading in ATE at the test temperature and X equals the equivalent DUT temperature.

$$Y = mX + b \quad (1)$$

Getting the delta between the target test temperature and the calculated X will result in the temperature error between the handler temperature and the DUT temperature. Lastly, the average Temperature Error (TempErr) per site is recorded and logged for the next part of the evaluation as indicated in Equation (2) where N is the total number of golden units which in this study is 20.

$$TempErr = \frac{(\sum(Test\ Temperature - X))}{N} \quad (2)$$

The calculated temperature offsets are -0.34 for Site 1, -0.38 for Site 2, 0.85 for Site 3, and 0.84 for Site 4.

C. *System Evaluation, Data Analysis, and Correlation*

The calculated temperature error was adjusted to the ATE handler used during data gathering. This will now be analyzed by running the 20 golden units through the ATE randomly across all sites.

Fig. 12 below shows the result of the passing readback data plotted within the calculated Upper Statistical Limit (USL) and Lower Statistical Limit (LSL) from the bench reference data of the same 20 golden units. The USL and LSL are based on the allowable and strict +/- 3°C temperature window.

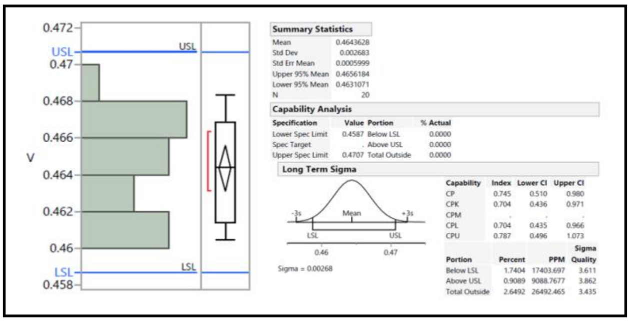
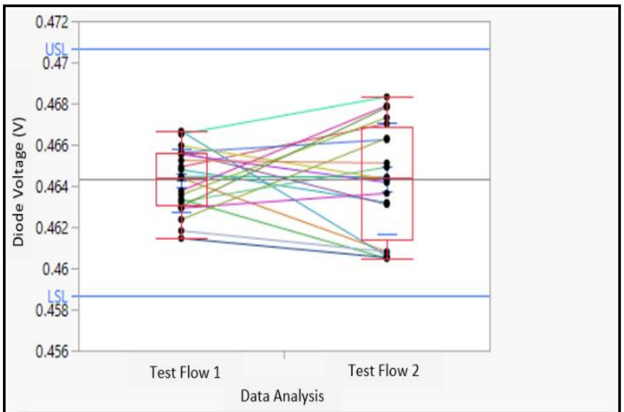


Figure 12. Golden units histogram on calibrated handler.

The plot in Fig. 13 displays the 20 temp calibration units tested on different test time length to check the variability caused by the test time. Test Flow 1 had ~2.3sec total test time and Test Flow 2 had ~0.2sec both with 4-site enabled testing. It has been noticed that lesser Standard Deviation (SD) for longer test time by 0.0011 only and all 20 golden units passed for both test flows.



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
Test Flow 1	0.461472	0.461893	0.463075	0.464437	0.465614	0.466468	0.466665
Test Flow 2	0.460493	0.46054	0.461396	0.464394	0.466855	0.467898	0.468331

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Test Flow 1	20	0.4642736	0.0015233	0.0003406	0.4635607	0.4649865
Test Flow 2	20	0.4643628	0.002683	0.0005999	0.4631071	0.4656184

Figure 13. Serial number match plot of two test flows with different test time.

To compare the diode voltage results of the recently calibrated test handler (Handler A) versus 3 test handlers (Handler B, Handler C, and Handler D) that have been calibrated statically, 350 units each from 3 different fabrication lot namely Lot 1, Lot 2 and Lot 3 previously tested at Handler B, C and D respectively were all then tested at Handler A.

Below Table II shows the standard deviation of the diode voltage across each lot. Results show up to 8x better SD on the newly calibrated handler.

TABLE II. STANDARD DEVIATION OF THE 3 LOTS ACROSS DIFFERENT HANDLERS

Lot 1		Lot 2		Lot 3	
Handler A	**Handler B**	**Handler A**	**Handler C**	**Handler A**	**Handler D**
0.0011	0.0057	0.0011	0.0078	0.0012	0.010

Fig. 14 shows the plotted serial number matching of the handlers along with the quartile plot equivalent.

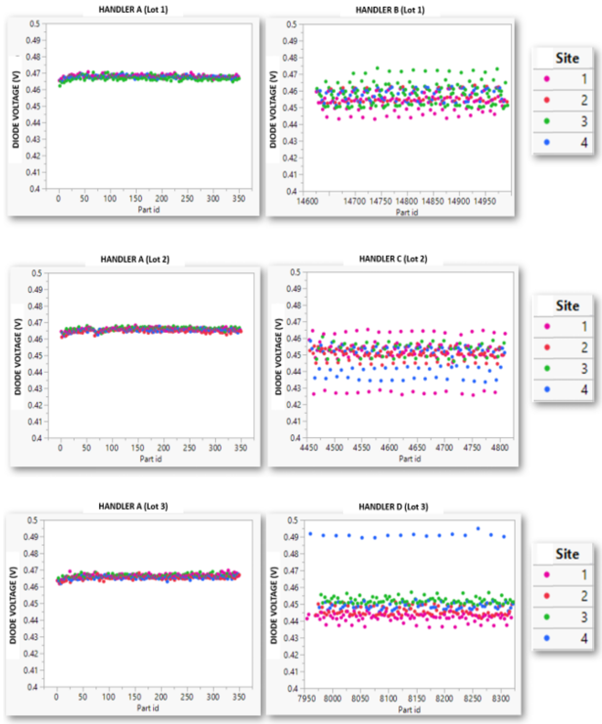


Figure 14. Plot distribution of the correlation units of the 3 lots in diode voltage parameter on the newly calibrated handler vs. other handlers.

V. CONCLUSION

The study was able to successfully characterize the diode voltage of the MEMS accelerometer to calibrate test temperature on the final test stage across all 4 sites using linear regression. In parallel, an automated calculator of offset temperature or temperature error between the handler test temperature and the DUT temperature was effectively developed from all the gathered data. From the results of the correlation between the bench reference data and the gathered ATE data of the 20 golden units where Test Flow 1 had 2.3sec total test time and Test Flow 2 had 200 milliseconds both with 4-site enabled testing, it was validated that all DUT temperature is within acceptable temperature window of +/- 3°C, also less standard deviation for longer test time by only 0.0011 and all 20 golden units passed for both test flows. Additionally, based from the results of the comparison of the newly calibrated test handler using the voltage-temperature relationship which had 0.0011, 0.0011, and 0.0012 SD of data and the static calibrated test handlers which had 0.0057, 0.0078, and 0.010 SD of data for each lot 1, 2 and 3 respectively show up to 8x improvement in SD of the DUT temperature in ATE.

VI. RECOMMENDATION FOR FURTHER STUDY

For future research, the authors would like to recommend the use of the handler communication for faster data logging of handler temperature. This would make the temperature calibration easier and more user-friendly once handed over to someone else. Also, as the developed code is currently capable up to 4-site testing, this can be improved by capturing more sites if needed depending on the user's test requirement.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Arianne Marie M. Holgado lead, conceptualized, and conducted the majority research study including the ATE testing & data gathering, hardware and software evaluation & development and all the data analysis and presentation; Jon Rainiel R. Jimenez gathered the bench reference data; Christopher M. Salazar, Glenn V. Magwili and Febus Reidj Cruz are the technical contributors and advisers; all authors had approved the final version.

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