Application Note

Using a PCB Copper Trace as a Current-Sense Shunt Resistor

Paul Stanfel, Mitch Morse

Current and Position Sensing

ABSTRACT

Current sense resistors are used to accurately and precisely measure current flowing through a load. To properly make this measurement, the resistor (also known as a shunt resistor) needs to be placed in series with the load. However, for very large currents, using shunt resistors for measuring current has some drawbacks. Since power dissipation varies proportionally to the square of the current, shunt resistors in series with loads that draw large currents can quickly become inefficient in that they dissipate power that could have been delivered to the load and more robust resistors are required to handle the power. This application note details the advantages and disadvantages of using a section of PCB copper trace as a shunt resistor in place of a more conventional surface-mount technology (SMT) shunt resistor. In practice, although a copper trace is much less expensive than an SMT resistor, it is highly susceptible to temperature fluctuations that must be accounted for to make accurate current measurements, as well as PCB manufacturing tolerances that may not be as tightly controlled and well documented as those of SMT resistors.

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1 Experimental Procedure

The procedure used to determine the viability and performance of using a copper trace as a shunt resistor involved testing several different copper trace widths, lengths, and geometries. The experimental setups are shown in Figure 1-1 and Figure 1-2. These two boards are collectively referred to as Revision A.

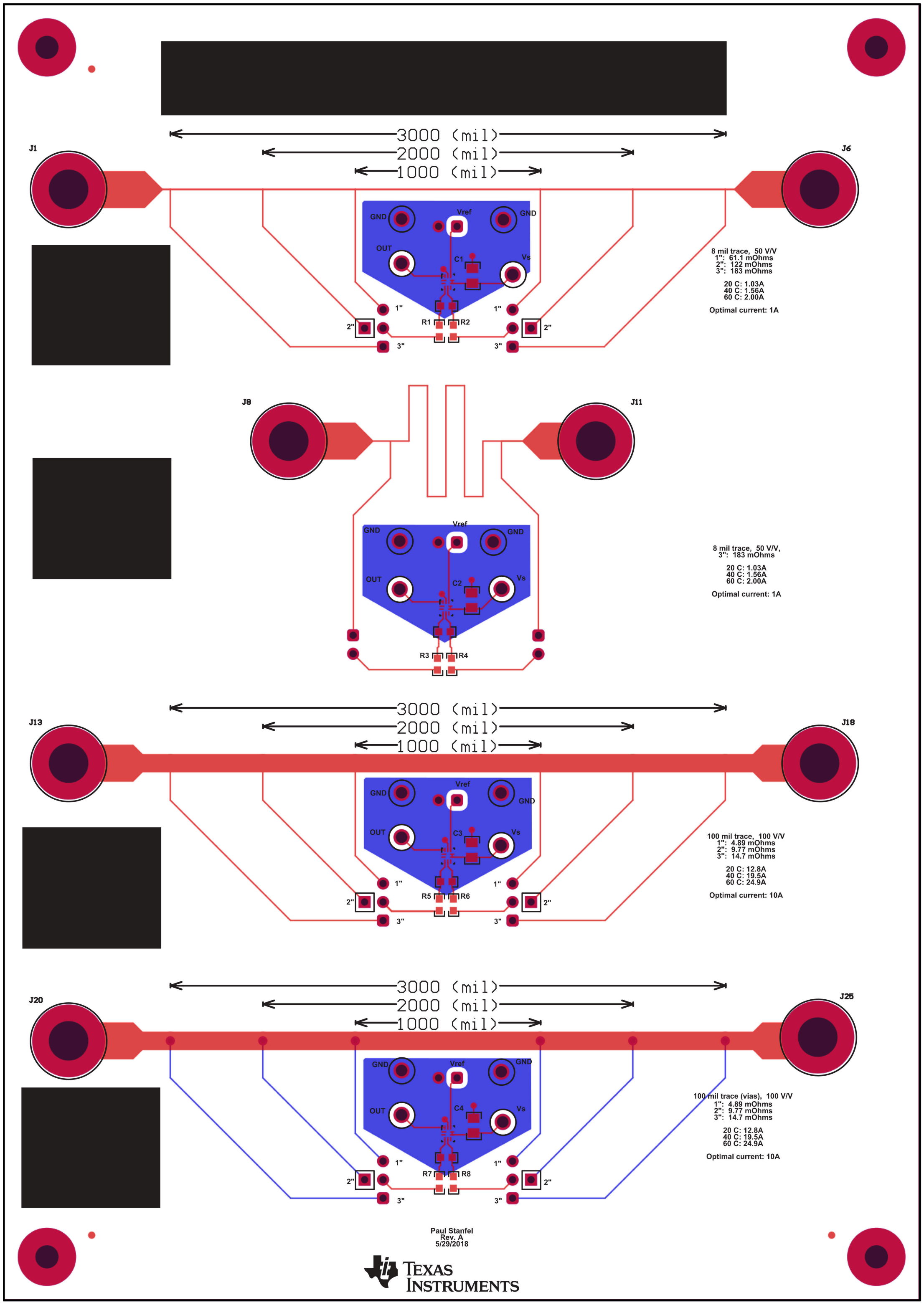


Figure 1-1. First Board of Revision A

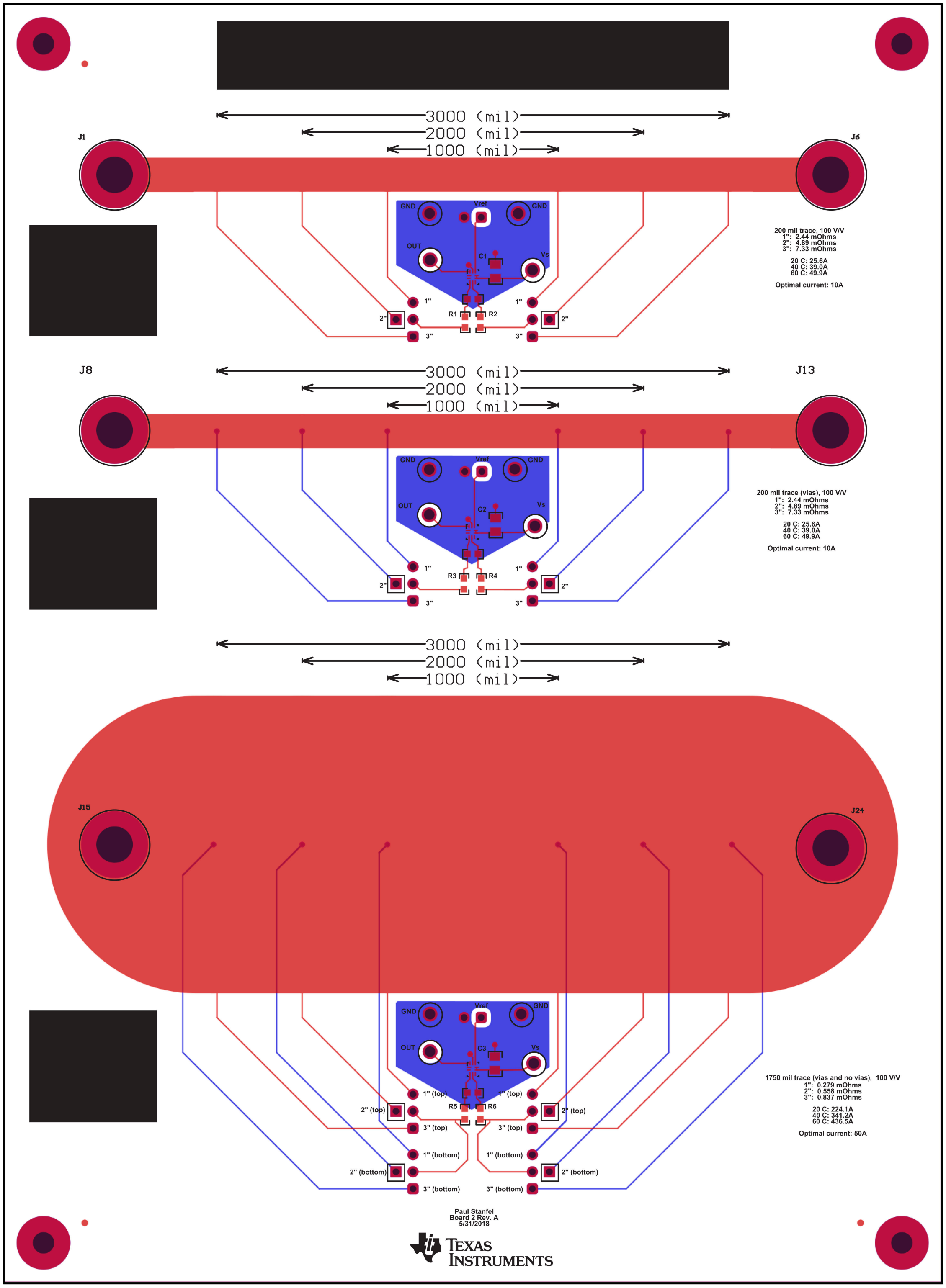


Figure 1-2. Second Board of Revision A

In total, four trace widths were tested: 8 mil, 100 mil, 200 mil, and 1750 mil. Each of these traces was tested at one, two, and three inch lengths with current flowing through them. In addition, each trace was tapped from the bottom of the trace (lower edge of the trace on the red layer) and from the center through vias to another layer (blue layer). *Tap off points* in this document refer to locations on the copper traces across which the voltage is measured using a differential amplifier. If the temperature and dimensions are known, the resistance between the two points can be calculated. Tap off points were chosen in the bottom and in the middle of the traces to investigate the impact of sense line location on the voltage measurement. The amount of current flowing through a conductor varies inversely with the resistance of the wire, meaning that measuring voltage in the center should theoretically yield a different result, since current would have to travel through more copper and therefore more resistance to reach the bottom of the trace as opposed to the center. Testing multiple lengths by using different tap points on the trace demonstrates the linearity of the trace. If the trace resistance behaves linearly, the three-inch tap off points should produce a resistance three times that of the one-inch tap off points. Also visible in Figure 1-1 is what is referred to as the *square shape* geometry (the trace second from the top). This is an 8-mil trace that is intended to examine the effects of changing the path of current on the overall resistance measurement.

The copper trace shunt tap off points are connected to an INA190 instrumentation amplifier through copper trace sense lines. The INA190 series of devices are voltage-output current-shunt monitors (also called current-sense amplifiers) that are commonly used for overcurrent protection, precision current measurement for system optimization, or in closed-loop feedback circuits. This series of devices can sense drops across shunts at common-mode voltages from –0.1 V to +40 V, independent of the supply voltage. Five fixed gains are available: 25 V/V, 50 V/V, 100 V/V, 200 V/V, or 500 V/V. The INA190 was chosen for its low input bias current, which increases the accuracy of the voltage measurement. For each trace, the INA190 output was recorded at each point (one, two, and three inches stemming from the bottom and from the center of the trace) at several known currents and using the current and the gain value of the amplifier, converted to a resistance measurement. The maximum current level to be pulled through each trace was determined using a current width calculator from the manufacturer. Four separate currents (1 A, 5 A, 10 A, and 50 A) were used to calculate the minimum trace widths to stay within a 20°C trace temperature rise. These widths were rounded up to obtain a trace width that could safely handle the given current, and these currents were in turn defined to be the maximum current that a particular trace would be tested with. The 8-mil trace takes 1 A, the 100-mil trace takes 5 A, the 200-mil trace takes 10 A, and the 1750-mil trace takes 50 A. INA190 gain settings were chosen to avoid saturation of an ideal copper trace resistor with a given maximum current flowing through it, assuming a supply voltage of approximately 5 V. The 100-mil, 200-mil, and 1750-mil traces all used the INA190 A3 with a gain of 100 V/V, while the 8-mil trace used the INA190 A2 with a gain of 50 V/V.

Calculating the resistance from a given INA190 output made it possible to see how the copper trace resistance changed with increasing current levels. Additionally, these tests were repeated in a temperature-controlled environment at four different ambient temperature levels: 0°C, 25°C, 55°C, and 85°C. The 25°C setting in this case, while conventionally taken to be room temperature, differs from what is referred to here as room temperature in that 25°C was the temperature controlled value, and *room temperature* refers to measurements taken out of the temperature-controlled environment. Testing at four different temperature levels gives an idea of how the resistance changes with temperature. For these tests only the three-inch test points were used, but once again both the center and bottom tap offs were tested.

Current step measurements were obtained by adjusting an electronic load in series with the trace to pull the desired current level. To achieve precise results, the voltage across a precision resistor in series with both the traces and the electronic load was measured using a multimeter to accurately determine how much current was moving through the trace. Each trace was tested initially at 0 A as specified by the electronic load, although the actual current value flowing through the trace as measured by the resistor and multimeter combination varied across a small range of positive and negative current values. The common mode voltage was set to approximately 5 V.

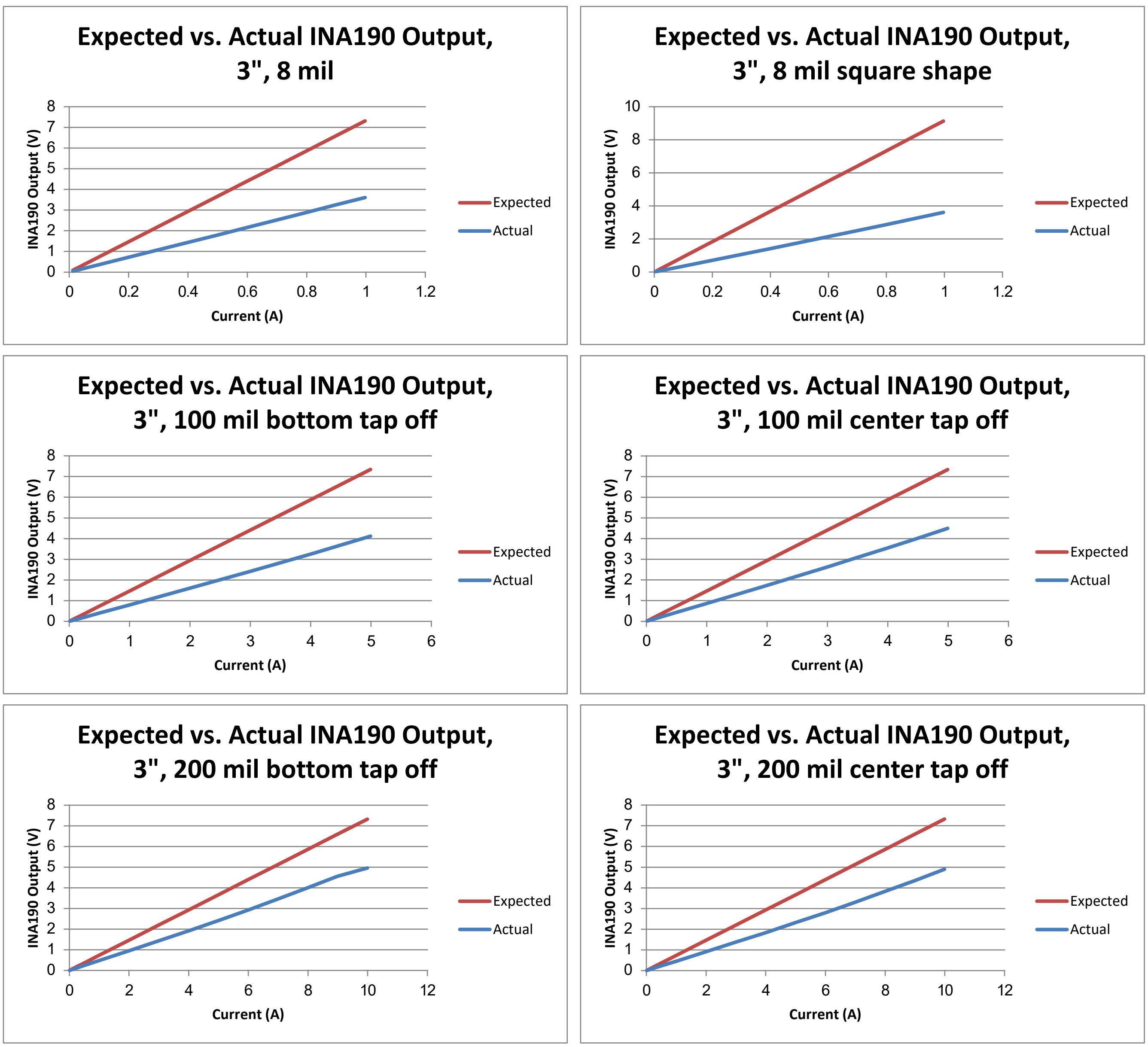
Although not visible in Figure 1-1 and Figure 1-2, a piece of thermally-conductive tape was used to attach the TMP235 temperature sensor to the middle of each trace. The TMP23x devices are a family of precision CMOS integrated-circuit linear analog temperature sensors with an output voltage proportional to temperature. This sensor was covered in thermally-resistive tape to further increase contact with the trace and insulate from the surrounding environment. This sensor obtains data about the temperature of the trace to determine how temperature affects trace resistance and performance. Temperature data obtained at the 0 A current step was used as a baseline temperature measurement and is intended to account for any variables that might cause discrepancies between the trace temperature and the ambient temperature, especially in the more controlled environment.

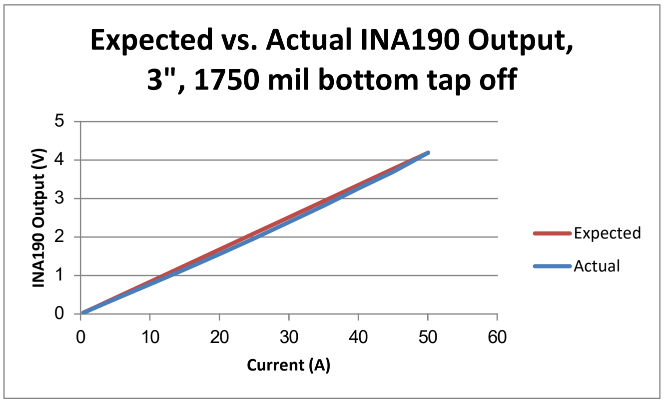
Results are grouped by whether or not they were obtained in a temperature-controlled environment. The process to obtain data is relatively straightforward. For room temperature measurements, the procedure involved incrementally stepping from 0 A to the maximum current level for each trace following a roughly logarithmic scale. Upon moving to the next current step, INA190 outputs were recorded for the one-, two-, and three-inch locations. Then, using the TMP235EVM evaluation software, temperature output from the TMP235 sensor was monitored until it ceased increasing. At this point, 50 temperature samples were recorded at a 2-Hz sampling rate and averaged to determine the trace temperature. During the course of testing it was observed that a potentially non-trivial temperature rise occurred between the last tap off tested and the recording of temperature, meaning that INA190 outputs could have possibly changed during the temperature stabilization process. For this reason, the procedure was modified slightly for the temperature-controlled tests. Since these tests took place in a temperature chamber, the TMP235 was first used to make sure that the trace had equalized with the ambient chamber temperature before any testing began. Then, a reduced number of current steps were used to again sweep from 0 A to the maximum. However, in this case, no values were recorded until both the INA190 output and the TMP235 output had stabilized. Results from the two testing setups are detailed in Section 2.

2 Results

2.1 Room Temperature

Because the precise current measurement was known for each current step, it is possible to determine what the INA190 output for each trace should be using a current trace resistance calculator to calculate the theoretically ideal resistance for each trace of given width and length. Temperature data obtained at the 0 A current step was interpreted as the ambient temperature and was factored into this theoretically-ideal resistance value. Traces are assumed to be 1 oz copper thickness. Analyzing the deviation from this expected value can give insight into the feasibility of using copper as a shunt resistor. Figure 2-1 shows the plots of these discrepancies for all measured traces at room temperature (uncontrolled temperature environment) for the three-inch measurement. These plots were almost identical for the one- and two-inch locations and are omitted here. Table 2-1 shows the average error for each trace. These errors excluded the percent error value for 0 A, as this current level was so small that some traces had percent errors near 20000%, due in part to the offset error of the INA190. *Board 1* and *Board 2* in Table 2-1 refer to different iterations of the same revision, as each revision consisted of three boards, each with the same layout.





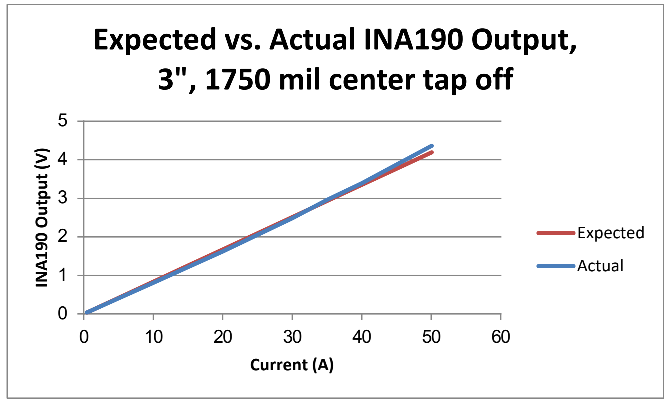


Figure 2-1. Expected vs Actual INA190 Output for Eight Trace Configurations

Table 2-1. Average Percent Error - Room Temperature

* The square shape trace had only one tap off point at three inches.

Trace	Average Percent Error			Average
	1”	2”	3”	
8 mil	–51.95%	–53.64%	–53.20%	–52.93%
8 mil square*	–	–	–58.01%	–58.01%
100 mil bottom tap off, board 1	–43.08%	–44.20%	–48.73%	–45.34%
100 mil bottom tap off, board 2	–54.77%	–55.05%	–54.52%	–54.78%
100 mil center tap off	–38.53%	–39.25%	–39.15%	–38.98%
200 mil bottom tap off	–31.10%	–32.09%	–32.36%	–31.85%
200 mil center tap off	–35.01%	–35.27%	–35.36%	–35.21%
1750 mil bottom tap off	1.48%	–1.25%	–3.44%	–1.07%
1750 mil center tap off	0.90%	–1.49%	0.58%	0.00%

The only trace width without significant error was the 1750-mil trace. It should be noted that at low current levels (less than 1 A), the 1750 mil had positive error, but from there to 50-A errors became negative. All other traces had very large errors that were; however, remarkably consistent. Also, discrepancies between measurements made on board 1 and board 2 were noted, as shown with the two instances of the *100 mil bottom tap off* data points. Finally, measurements made at the center of the trace were different from those made at the bottom. However, this effect is not predictable. Some were better approximations, but some were worse. The 100-mil trace showed the largest difference, with 6.36% difference in error. The 1750-mil trace was also a better approximation at the center tap off.

To determine the cause of the large error, one of the boards was cut in half and analyzed by a Scanning Electron Microscope (SEM). SEM analysis of the trace cross-section showed that trace thickness was much larger than the assumed 1 oz/ft^2 copper that was ordered. One of the trace cross-sections is shown in Figure 2-2, and the actual trace thicknesses are displayed in Table 2-2.

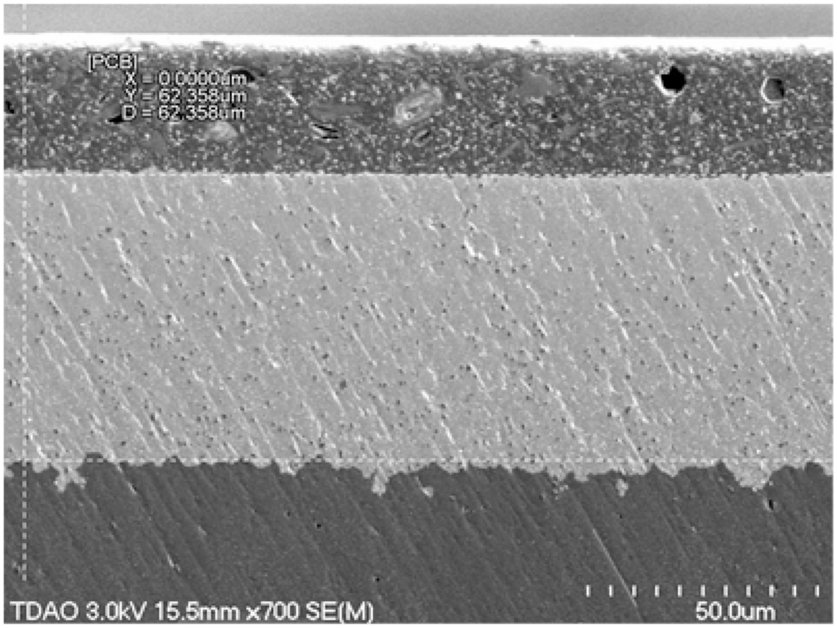


Figure 2-2. Cross-Sectional View of the 100-mil, Bottom Tap Off Trace

Table 2-2. Trace Thicknesses Determined by SEM Analysis

PC Board	Thickness (µm)	Thickness (oz/ft^2)	Width (mm)	Width (mil)
100 mil bottom	63.5	1.82	2.50	98.4
100 mil center	62.4	1.79	2.28	89.8
1750 mil	41.7	1.20	44.58	1755.1
200 mil center	62.1	1.78	4.78	188.2
200 mil bottom	61.2	1.76	4.33	170.5

As shown in Table 2-2, some traces were almost twice as thick as was expected compared to the ideal 1 oz (34.8 µm). A thicker trace decreases the resistance, explaining why some of the trace percent errors were in the –40% to –50% range.

Contacting the PCB manufacturer revealed the reason that the smaller copper traces were so much thicker than expected. Due to the process of plating copper on the outer layer of a PCB, patterns with less surrounding copper will be thicker in general. Thus, for the 100- and 200-mil traces, since they are relatively isolated from other copper patterns, the thickness is large. The 1750-mil trace, however, is large enough to reduce the impact of this effect and is much closer to what is expected. This is borne out by examining standards released by the Association Connecting Electronics Industries (IPC). IPC standards mandate a minimum copper trace thickness, but they do not specify the maximum. Essentially, this means that any trace used as a current shunt will always be less than the expected resistance, with a more prominent effect occurring for smaller trace widths. The relevant IPC standard is shown in Figure 2-3. (Table reproduced with permission from IPC).

Minimum Surface Conductor Thickness = a + b - c

Where:

a = Absolute copper foil minimum (IPC-4562 nominal less 10% reduction).
b = Average copper plating thickness (e.g. 20µm [787 µin] for Class 1 and Class 2; 25 µm [984 µin] for Class3).
c = A maximum variable processing allowance reduction.

Table 3-14 External Conductor Thickness after Plating

Weight[1,4]	Absolute Cu Min. (IPC-4562 less 10% reduction) (µm) [µin][5]	Plus average plating for Class 1 and 2 (20 µm) [787 µin][2] FOR REFERENCE PURPOSES ONLY	Plus average plating for Class 3 (25 µm) [984 µin][2] FOR REFERENCE PURPOSES ONLY	Maximum Variable Processing Allowance Reduction[3] (µm) [µin] FOR REFERENCE PURPOSES ONLY	Minimum Surface Conductor Thickness after Processing (µm) [µin]	
					Class 1 & 2	Class 3
1/8 oz.	4.60 [181]	24.60 [967]	29.60 [1,165]	1.50 [59]	23.1 [909]	28.1 [1,106]
1/4 oz.	7.70 [303]	27.70 [1,091]	32.70 [1,287]	1.50 [59]	26.2 [1,031]	31.2 [1,228]
3/8 oz.	10.80 [425]	30.80 [1,213]	35.80 [1,409]	1.50 [59]	29.3 [1,154]	34.3 [1,350]
1/2 oz.	15.40 [606]	35.40 [1,394]	40.40 [1,591]	2.00 [79]	33.4 [1,315]	38.4 [1,512]
1 oz.	30.90 [1,217]	50.90 [2,004]	55.90 [2,201]	3.00 [118]	47.9 [1,886]	52.9 [2,083]
2 oz.	61.70 [2,429]	81.70 [3,217]	86.70 [3,413]	3.00 [118]	78.7 [3,098]	83.7 [3,295]
3 oz.	92.60 [3,646]	112.60 [4,433]	117.60 [4,630]	4.00 [157]	108.6 [4,276]	113.6 [4,472]
4 oz.	123.50 [4,862]	143.50 [5,650]	148.50 [5,846]	4.00 [157]	139.5 [5,492]	144.5 [5,689]

Note 1. Starting foil weight of design requirement per procurement documentation.
Note 2. Reference: Average Cu Plating Thickness
Class 1 = 20 µm [787 µin] Class 2 = 20 µm [787 µin] Class 3 = 25 µm [984 µin]
Note 3. Process allowance reduction does not allow for rework processes for weights below 1/2 oz. and above, the process allowance reduction allows for one rework process.
Note 4. For copper foil above 4 oz., utilize the formula provided in 3.6.2.15.
Note 5. For foil weights not listed in Table 3-14, the absolute copper minimum shall be calculated using the following algorithms. For microns (µm) use [(34.3 X Weight) X 0.9] and for [µin] microinches use [(1.35 X Weight) X 0.9] X 1000.

Figure 2-3. IPC Standard Specifying Minimum but not Maximum PCB Copper Trace Thickness

The fact that trace width can vary even on the same board makes it difficult to determine whether or not the square shaped trace affects the trace resistance, although this comparison was reexamined in the second revision as detailed in Section 3.

Using the data from Table 2-2, the estimates of trace resistance were modified to attempt to better match the experimental results. Instead of 1-oz copper, the thickness was set as the entry in Table 2-2. Also, since previous resistance measurements assumed 25°C ambient temperature, the new temperature was set to be whatever temperature the TMP235 read at the 0-A current step. Table 2-3 shows the adjusted results.

Table 2-3. Average Percent Error – Room Temperature, Adjusted

Trace	Average Percent Error			Average
	1"	2"	3"	
100 mil bottom tap off	–10.11%	22.22%	0.61%	4.24%
100 mil center tap off	–13.09%	18.92%	6.69%	4.17%
200 mil bottom tap off	3.14%	1.70%	1.18%	2.01%
200 mil center tap off	9.38%	8.68%	8.61%	8.89%
1750 mil bottom tap off	21.87%	18.80%	16.10%	18.92%
1750 mil center tap off	21.17%	18.51%	20.92%	20.20%

After the adjustment process, the traces decreased significantly in error with the exception of the 1750-mil trace which experienced a substantial increase in error. The differences between center and bottom tap off points as noted in Table 2-1 are also much less pronounced and, in the case of the 1750-mil trace, are even reversed.

Because copper traces experience heating as current passes through, the extrapolated resistance of the copper traces were recorded with respect to the current passing through them. Potential for error exists in the fact that, throughout the measurement process, the trace might have continued to heat up as noted in Section 1. The impact of additional trace heating during the temperature equalization process would have most likely resulted in a difference of around 0.5 mΩ at the very maximum, based on observations made in the later tests. Plots of how trace resistance changes with current are shown in Figure 2-4. Temperature data is unavailable for the 8-mil traces.

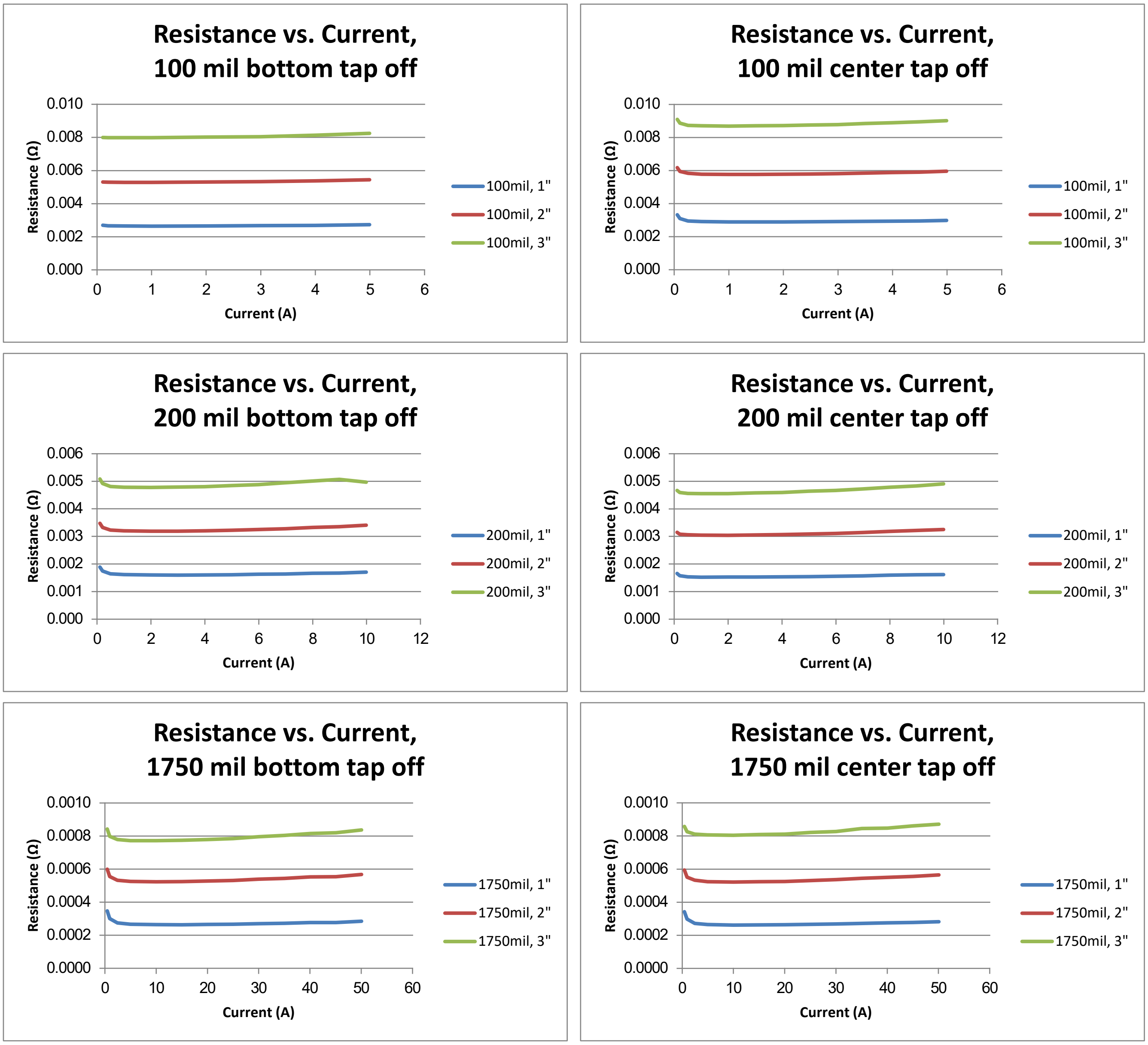
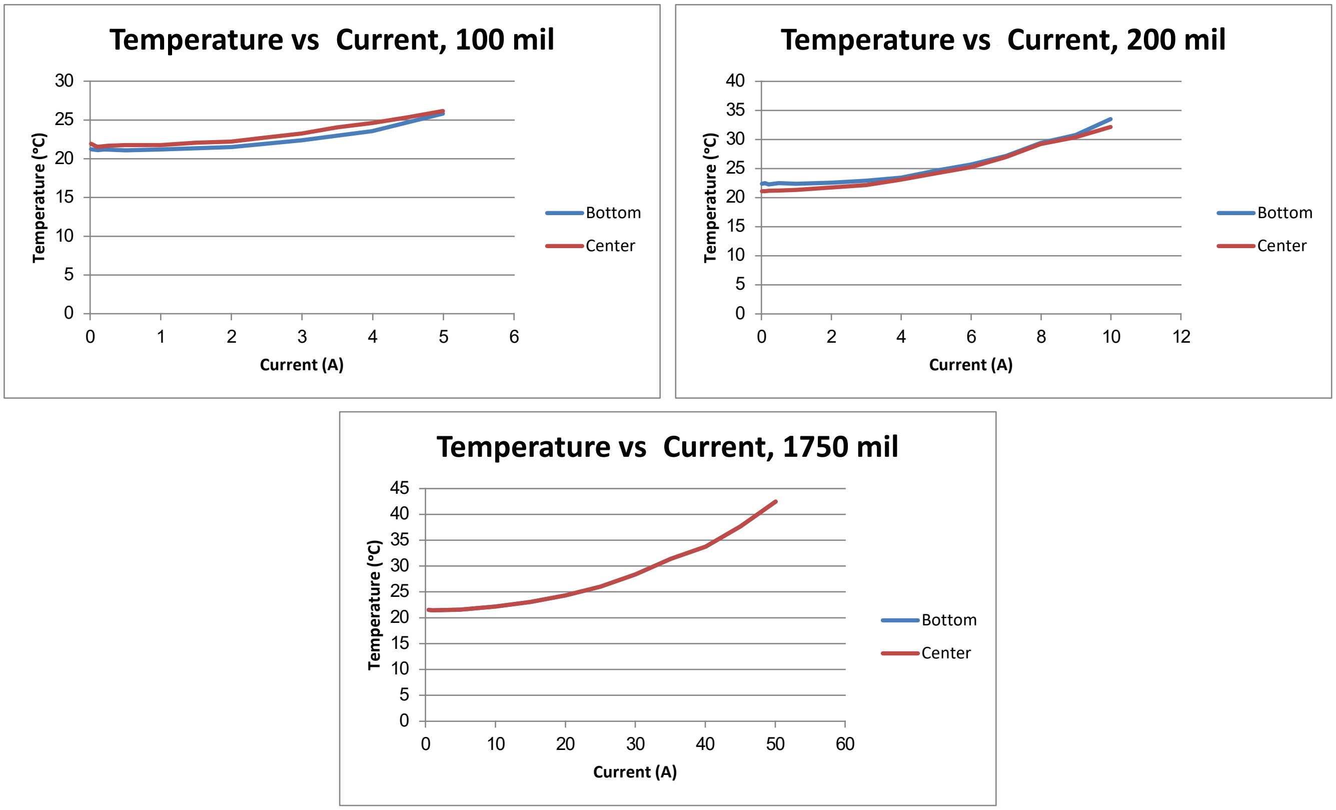


Figure 2-4. Resistance vs Current Plots for Six Trace Configurations

These plots demonstrate that for low current values, the trace resistance exhibits nonlinear behavior, but after a certain point the resistance changes more or less linearly with current. This is most likely due to the INA190 offset error which has a larger impact when the output is smaller. The point at which a trace begins to behave linearly is dependent on the size of the trace, as the 100-mil trace entered this region around 0.1 A, the 200-mil trace around 0.2 A, and the 1750-mil trace around 2.5 A. This is important information to keep in mind, as it demonstrates that simply running current through the trace affects the resistance. Any application of a copper trace must take into account the fact the time needed for the trace resistance to stabilize in this manner.

Finally, the temperature sensor attached to the board gave indication of how the trace temperature changed as the current increased. A strong upward trend was expected and for the most part obtained. For smaller traces, full contact with the sensor could not be ensured, and the temperature results may be skewed by the surrounding PCB. However, temperature data was not recorded until the trace temperature as recorded by the sensor had ceased increasing, so these values should theoretically represent a stable reading after all change has taken place. Plots of the trace temperature are shown in Figure 2-5.



Note

The 1750-mil curves are virtually indistinguishable.

Figure 2-5. Temperature vs Current Plots for Three Trace Configurations

Maximum current values were chosen to cause approximately 20°C of temperature rise from the ambient. This was not the case for many of the plots in Figure 2-5. Similar trace widths did, however, experience similar temperature rises. It is most likely the case that this lack of expected temperature rise is the result of the manufacturing tolerances discussed previously and otherwise is not significant, as the temperature rise calculations involved several assumptions and also rounding error.

2.2 Temperature Chamber Testing

To determine the effects of temperature variation on a copper trace shunt resistor, the traces were placed in a temperature chamber to control the ambient temperature. It should be noted that fewer data points were taken in the chamber due to the added time needed for the board to reach the chamber temperature between trace measurements. Also, only the three inch separation is considered. As in the case of the room temperature measurements, it is possible to plot how resistance changes with current. Similar trends were observed relative to room temperature, and the plots are shown in Figure 2-6. The 100-mil, bottom tap off plots are used to demonstrate the changes across temperature, as every trace width performed similarly.

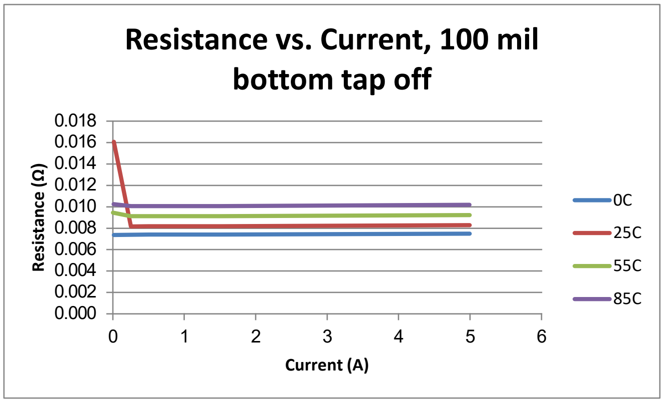


Figure 2-6. 100-mil Bottom Tap Off Resistance vs Current Plots Across Four Temperatures

The plots in Figure 2-6 show that, as ambient temperature increases, the resistance also increases which is consistent both with what is expected and previous results. Figure 2-7 demonstrates how much the resistance changes with temperature by plotting the maximum recorded resistance for each trace with respect to the ambient temperature. The 0 A measured resistance is not included.

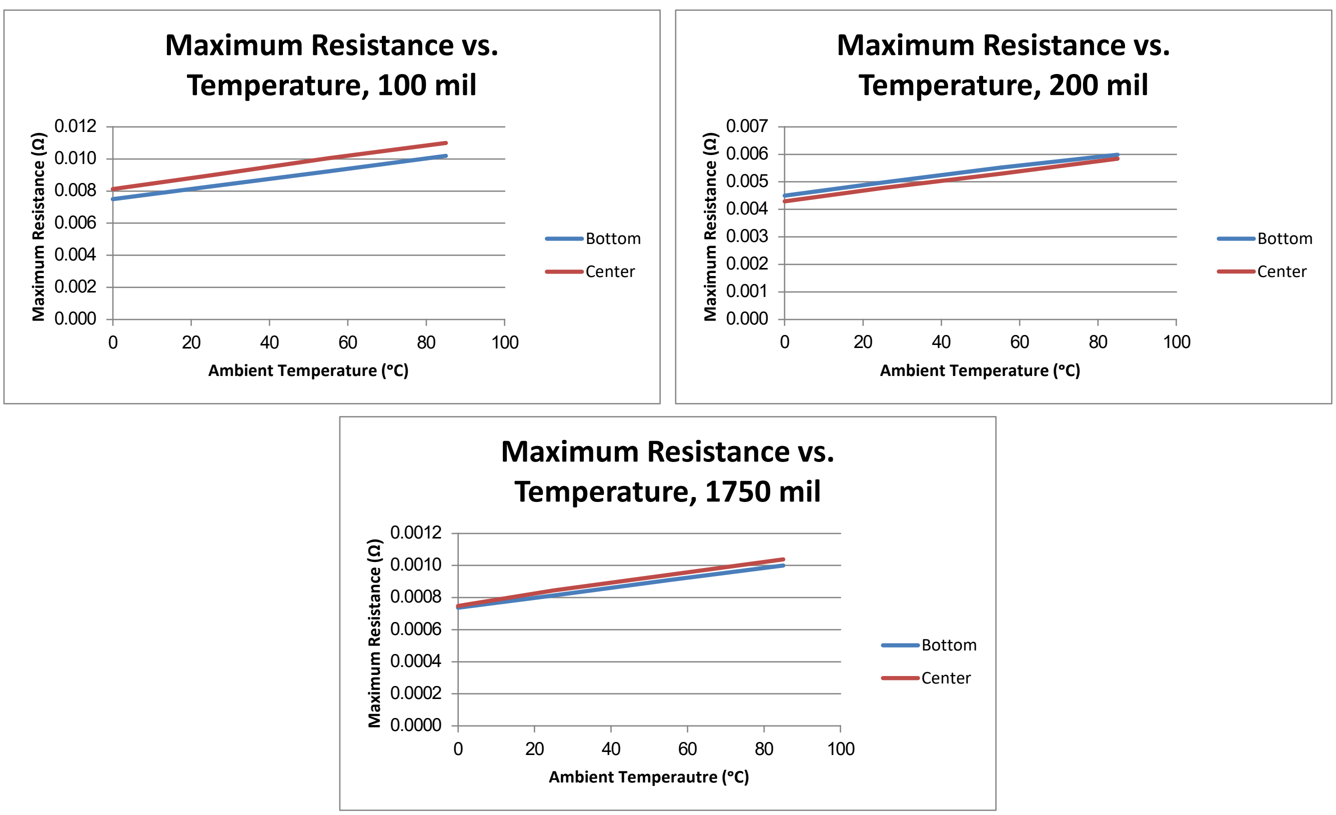


Figure 2-7. Maximum Resistance vs Temperature for Three Trace Configurations

The plots in Figure 2-7 indicate that as ambient temperature increases, so does the measured resistance. This is an important factor to keep in mind, as the operating temperature of an application using a copper trace current shunt must be taken into account for proper calibration. As in the case of the room temperature environment, the average percent errors, this time across a range of temperatures, were calculated and are displayed in Table 2-4.

Table 2-4. Average Percent Error - Temperature Controlled

Trace	Average Percent Error				Average
	0°C	25°C	55°C	85°C	
100 mil bottom tap off	–49.51%	–44.19%	–37.75%	–31.31%	–40.69%
100 mil center tap off	–45.34%	–39.47%	–32.25%	–25.63%	–35.67%
200 mil bottom tap off	–39.70%	–33.17%	–25.74%	–20.07%	–29.67%
200 mil center tap off	–42.29%	–35.89%	–28.71%	–21.30%	–32.05%
1750 mil bottom tap off	–13.72%	–4.75%	6.39%	16.92%	1.21%
1750 mil center tap off	–10.72%	–1.29%	10.24%	21.46%	4.93%

The values in Table 2-4 demonstrate potential design considerations. All traces except the 1750-mil trace experienced a decrease in errors as temperature increased. The 1750-mil trace had its lowest error at 25C. This is because resistance increases with temperature, and since all of the traces with the exception of the 1750-mil trace started at significantly lower resistances than expected due to the PCB manufacturing process, it makes sense that as the temperature and resistance rises they approach the ideal value. For applications that might be significantly warmer than 25°C, a smaller trace might be acceptable depending on the temperature rise.

3 Hardware Revision B

The results given in Section 2 initially imply that copper trace shunt resistors are not feasible for practical use, given the inability to control the true thickness of the trace and tendency of copper to change resistance as current flows through it. However, Figure 3-1 displays a second design revision with an alternative experimental setup that could demonstrate how to avoid the issues discussed previously. This design is referred to as Revision B.

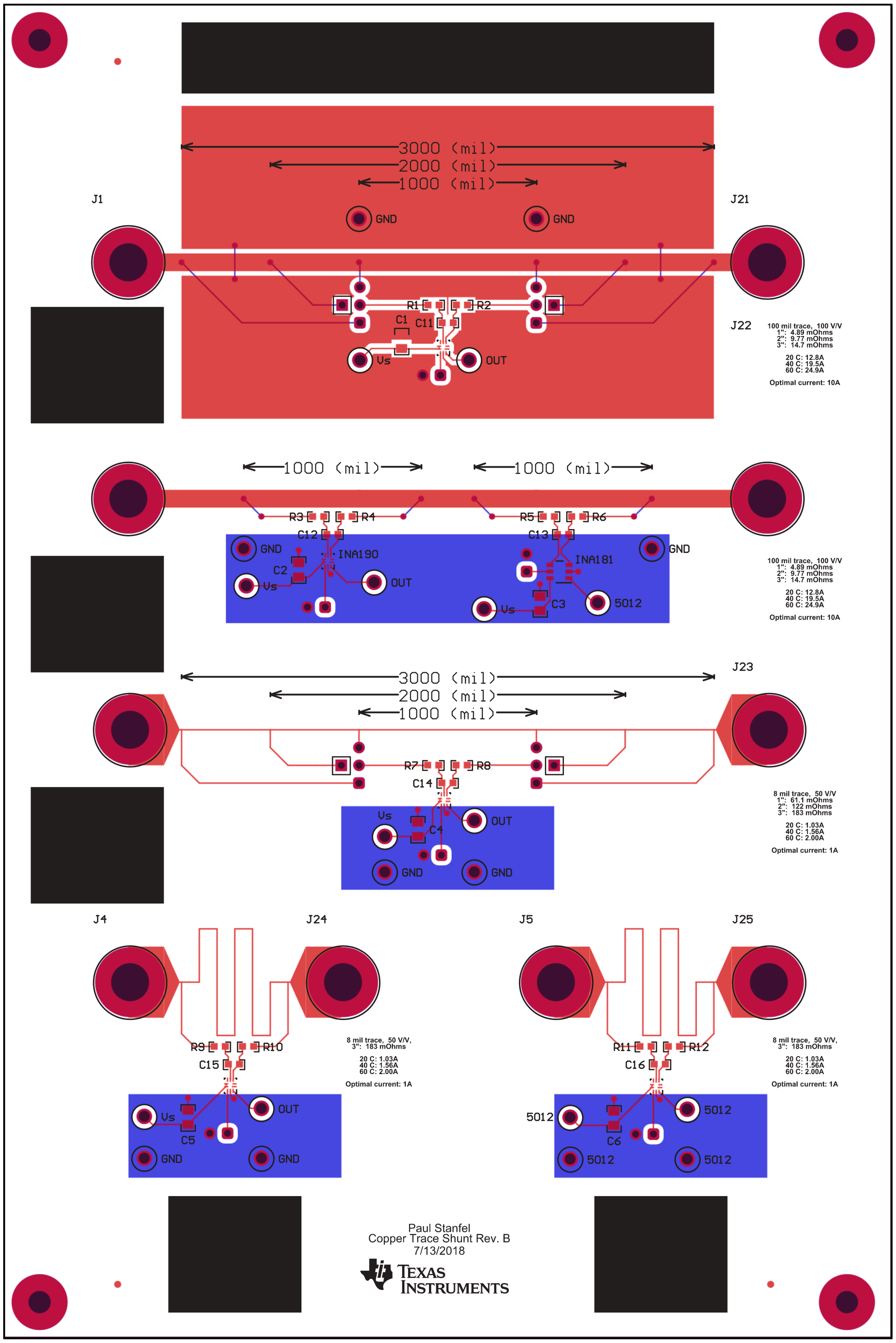


Figure 3-1. Revision B Board

The trace at the top (see Figure 3-1) attempts to add a large amount of surrounding copper (an extended ground plane) to the 100-mil trace to decrease the impact of the PCB manufacturing error. The second trace is a normal 100-mil trace that is measured by both the INA190, as in the first revision, and the INA181. The INA181 current-sense amplifier is designed for cost-optimized applications. This device is part of a family of bidirectional, current-sense amplifiers (also called current-shunt monitors) that sense voltage drops across current-sense resistors at common-mode voltages from –0.2 V to +26 V, independent of the supply voltage. The INAx181 family integrates a matched resistor gain network in four fixed-gain device options: 20 V/V, 50 V/V, 100 V/V, or 200 V/V. This matched gain resistor network minimizes gain error and reduces the temperature drift. The reason for comparing the INA181 to the INA190 is to analyze the possibility of using a copper trace shunt in conjunction with the lower cost INA181 to develop a less expensive but less accurate current-sense solution. For this trace, no attempt is made to regulate the thickness of the trace. Instead, a two-point calibration is used to try to accurately predict the output of the device regardless of what its actual thickness is. This kind of calibration is also tested with other trace widths. Finally, the last three traces in Figure 3-1 are repeated 8-mil traces, intended primarily to look at the variability in trace width within a single board.

Table 3-1 shows the percent error results for the 100-mil trace with an extended ground plane. The 100-mil trace errors from Table 2-1 are reprinted for comparison, as well as the 100-mil trace with no ground plane shown in Figure 3-1. As before, “board 1” and “board 2” refer to different boards in the same revision.

Table 3-1. Percent Errors for the 100-mil Reduced Thickness Trace

Trace	Average Percent Error			Average
	1”	2”	3”	
100 mil extended ground plane, board 1	–16.71%	–20.29%	–23.22%	–20.07%
100 mil extended ground plane, board 2	–18.25%	–21.43%	–24.64%	–21.44%
100 mil, board 1	–38.87%	–	–	–38.87%
100 mil bottom tap off	–42.96%	–44.08%	–48.38%	–45.14%
100 mil center tap off	–38.53%	–39.25%	–39.15%	–38.98%

The error is significantly reduced even when compared to a trace that is on the same board, but is still large. However, based on the results of testing multiple boards, it appears that the error is at least consistent. This could mean that this technique is feasible, but it is also possible that a different board from a different manufacturer would have a different error. In addition, the larger ground plane takes up a significant amount of space and essentially removes the advantages of using a smaller 100-mil trace as opposed to the 1750-mil trace, as the latter option is more accurate and occupies approximately the same area. The results of this experiment indicate that the more continuous the copper plane, the closer trace thickness is to the expected value and that obtaining a resistance of the correct value would require a very large trace.

The board was also used to determine the effectiveness of a simple calibration process which would save space. The curves shown in Figure 2-1 indicate that the discrepancy between expected and actual outputs could simply be treated as a gain error. Calibrating the trace with a low and a high current could theoretically allow for any outputs along the *Actual* curve to be predicted. This procedure is complicated by several factors. First, as shown in Figure 2-4, resistance changes as current moves through the trace. This means that the calibration curve can be skewed depending on when measurements are taken. In some cases, outputs settling times were recorded in excess of 5 minutes. Also, if there is significant variability of trace thickness between boards, calibration would be required for every board and a batch calibration process would suffer from inaccuracies. Finally, calibrating in this way does not allow for changes caused by temperature variation away from the calibration temperature.

To determine the feasibility of a two-point calibration method, the first step was to use a realistic procedure. Table 3-2 displays 4 possible setups, distinguished by how many data points were collected, whether or not the calibration output measurements were allowed to stabilize, and whether or not the test output was allowed to stabilize. Each setup was used to predict the output of the INA190 output with 2.5 A running through the trace. The percent error between this prediction using the calibration and the actual output is also given. These were obtained with the *plain* 100-mil trace in Figure 3-1.

Table 3-2. Possible Calibration Procedures to Account for PCB Thickness Error

Setup	Number of Data Points	Calibration Outputs Stable?	Test Output Stable?	Percent Error
Max. Data Points	4	Yes	No	–1.85%
Reduced Data Points	2	Yes	No	–1.24%
Reduced Temp. Effects	2	No	No	–0.58%
Max. Temp. Effects	2	No	Yes	–2.25%

The first setup took four calibration data points, three of which were in the low current range. This was the most unrealistic, as in a practical application it would most likely not be feasible to wait for four different calibration points to stabilize before recording them. Also, a real application would most likely always be dealing with a current that had been running through the trace long enough to bring it up to its equilibrium temperature, so recording the test output before it stabilizes is not the most accurate simulation of actual events. For this reason, the second and third setups are also not realistic. The fourth option represents what would probably be implemented: the minimum number of data points, with the shortest amount of time spent on waiting for the calibration process, and a test current that has been flowing for a long time. Unfortunately, this procedure has the largest error but is the only one that could realistically be implemented in large quantities.

To test the calibration process, the data points recorded were used to calculate the slope and intercept of the calibration curve. With these numbers, it is possible to backwards-calculate an output from the INA190 and predict the current. Because the actual current is known, calculating percent error reveals the effectiveness of the calibration. The first trace that was calibrated was the 100-mil trace used to obtain Table 3-2 data. The calibration currents used were 0.1 A and either 5 A or 10 A. Four test currents were used: 0.01 A, 2.5 A, 5.5 A, and 7 A. For each, the INA190 output was allowed to stabilize before recording. To thoroughly examine the capabilities of this technique, the 100-mil trace from revision B was used to predict INA190 outputs from the 200-mil trace of revision A. Table 3-3 and Table 3-4 show the results. The calibration data was taken from board 1, revision B.

Table 3-3. 100-mil Calibration Results

Board	Max. Cal. Point	Percent Errors			
		0.01 A	2.5 A	5.5 A	7 A
Board 1, Rev. B	5 A	–36.31%	–1.16%	2.11%	4.03%
Board 2, Rev. B	5 A	–12.72%	–1.58%	1.46%	3.53%
Board 1, Rev. A	5 A	–98.76%	–1.87%	1.98%	4.55%
Board 1, Rev. B	10 A	–20.52%	–4.57%	–1.49%	0.35%
Board 2, Rev. B	10 A	15.20%	–4.97%	–2.12%	–0.14%
Board 1, Rev. A	10 A	–81.22%	–5.25%	–1.62%	0.85%

Table 3-4. 100-mil Calibration Results for 200-mil Trace

Board	Max. Cal. Point	Percent Errors			
		0.02 A	5 A	10 A	20 A
Board 1, Rev. A	5 A	–79.87%	18.01%	24.96%	49.92%
Board 1, Rev. A	10 A	–55.87%	13.92%	20.54%	44.57%

Testing two different calibration points demonstrates how the calibration can be adjusted based on anticipated current. A 100-mil trace can handle 5 A while staying within a relatively arbitrary limit of 20°C of temperature rise. Calibrating to a higher current allows for more accurate predictions of larger currents, but the extrapolation of lower currents suffers. Also, accuracy of the calibrated prediction severely suffers when used for a trace of a different width and revision. This makes sense as more factors are introduced that can cause deviation from the calibration conditions.

This calibration procedure was also used for the trace with the extended ground plane, as well as the 8-mil trace. Table 3-5 and Table 3-6 show these results. The two calibration points used for the 8-mil trace were 0.02 A and 1 A.

Table 3-5. 100-mil Extended Ground Plane Calibration Results

* These currents caused saturation for some outputs and are left blank when this is the case.

Board	Max. Cal. Point	Length	Percent Errors			
			0.01 A	2.5 A	5.5 A*	9.5 A*
Board 1	5 A	1 in	800.08%	3.00%	4.57%	10.73%
		2 in	65.48%	–0.64%	2.29%	–
		3 in	–28.81%	11.92%	–	–
Board 2	5 A	1 in	796.22%	2.47%	3.63%	10.24%
		2 in	81.88%	–1.63%	0.75%	–
		3 in	–29.23%	10.39%	–	–

Table 3-6. 8-mil Calibration Results

* The first two boards used a current of 1.5A, while the last three used 1.2A to avoid output saturation.

Board	Percent Errors			
	0.005 A	0.5 A	0.95 A	1.5 A, 1.2 A*
Rev. B, Board 1, 1”	12.99%	–0.72%	0.89%	3.51%
Rev. B, Board 2, 1”	4.06%	–2.03%	–0.45%	2.00%
Rev. B, Board 2, 3”	9.91%	1.59%	2.71%	3.58%
Rev. B, Board 1, square	–1.85%	–14.46%	–12.97%	–11.69%
Rev. A, Board 1, square	–9.70%	–8.71%	–7.10%	–5.83%

Finally, the INA181 was used for calibration. The procedure was identical to the method used for the INA190, only with a different device. Only the 100-mil trace was examined using this calibration technique. Table 3-7 shows the results.

Table 3-7. INA181 Calibration Results

Board	Max. Cal. Point	Percent Errors			
		0.01 A	2.5 A	5.5 A	7 A
Board 1, Rev. B	5 A	–99.90%	–0.12%	2.24%	4.47%
Board 1, Rev. B	10 A	–99.90%	–2.93%	–0.71%	1.44%
Board 2, Rev. B	5 A	–52.27%	–0.89%	1.61%	3.66%
Board 2, Rev. B	10 A	–27.50%	–3.68%	–1.32%	0.66%

The data in the previous tables demonstrate several limitations of the two-point calibration process. Calibration points taken from one board usually were able to predict outputs from boards of the same revision. However, for boards of different revisions, the accuracy was significantly decreased due to PCB manufacturing variability over time. The INA181 also seemed to perform equal to or even better than the INA190. This suggests that it can be used in place of the INA190 with similar results, at least when calibration is being used to account for discrepancies.

Finally, revision B provided the opportunity to reexamine the effects of trace shape on resistance. Table 3-8 shows the results from these experiments, similar in format to Table 2-1.

Table 3-8. Average Percent Error: 8-mil Traces on Board 1

Trace	Average Percent Error			Average
	1”	2”	3”	
8 mil	–51.95%	–53.64%	–53.20%	–52.93%
8 mil square left	–	–	–58.01%	–58.01%
8 mil square right	–	–	–51.80%	–51.80%

While there are differences, it is difficult to determine whether these are due to any impact from the shape of the trace or simply because the thicknesses are different. The fact that the same shaped trace has a different average (right versus left) implies that this discrepancy is due to the same previously-discussed tolerances, or at least that any difference in resistance added by trace shape is not enough to overcome thickness variation.

All results showed a much larger percent error for very low current values, but this is to be expected due to the offset error of the INA190 and INA181. These would most likely be of concern even for a conventional SMT resistor.

4 Suggestions and Conclusion

There are several advantages to using copper traces in place of a normal shunt resistor. One advantage is the reduced cost of implementation. Another is the fact that they can handle large currents, depending on the size of the trace. This must be balanced against the fact that copper trace thickness is highly susceptible to variations in the PCB manufacturing process, and that temperature variation due to ambient conditions and current running through the trace can affect the resistance measurements.

Copper trace shunt resistors are not suitable for any application that requires a high degree of accuracy. The only way to assure that the trace resistance is reasonably close to what is expected is to use a very large continuous trace with no gaps. This is also the only trace that can be used to handle large currents.

Alternatively, for applications where cost is more important to optimize than accuracy, it is possible to use a two-point calibration method to account for manufacturing errors, but it is crucial to realize that the approximation afforded by the calibration becomes significantly worse as more boards are made, as PCB manufacturers are unable to completely control how much copper is plated on the board. The calibration prediction also gets worse for larger currents, as these currents heat the trace more and cause more deviation from the expected values.

Some factors proved to not be as important to implementing a copper trace shunt. No significant difference in measurement was noticed between tap off points, either at the bottom or the center. Also, trace shape appeared to not have much of an impact on the overall resistance of the trace, but this is difficult to prove conclusively.

Copper traces, while an inexpensive alternative to SMT shunt resistors, must be used with caution to measure current. A solution using this method can not be assured to behave as expected, and requires adjusting calibration constants to account for variability.

5 References

- IPC table from IPC-6012, reproduced with permission from IPC.

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